A Green Open Access Optical Distribution Network with Incremental Deployment Support

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***Abstract*—This paper proposes an optical distribution network (ODN) architecture for open access networks. The proposed scheme ensures co-existence of multiple business partners (BPs) e.g., service, network equipment, and infrastructure providers at different levels of the distribution network, along with physical-layer security. Further, physical-layer isolation is provided to each subscriber, preventing network disruption by malicious subscribers. The proposed open access ODN supports BPs with different granularities (sizes) and discourages monopoly; thus, allowing multiple BPs to co-exist. It also supports incremental deployability (ID) which allows the BPs to cope with an expanding user base. Thus, small BPs can take up a market share with reasonable initial investment and grow with differential expenditures. ID further allows us to incrementally scale up the power consumption as a function of the network load, making the architecture green. The proposed ODN is based on a passive optical network (PON) architecture resulting in low operational expenditures (OpEx) and high availability. Besides a new ODN architecture, a novel architecture for the optical line terminal (OLT), based on hybrid time and wavelength-division multiplexing (TWDM), is proposed. The BPs can adopt typical TWDM, wavelength division multiplexing, or the TWDM-based OLT architecture (introduced in this paper) over the proposed ODN.**

***Index Terms*—Bandwidth flexibility, green access networks, open access networks, passive optical networks.**

I. Introduction

THERE has been a steady growth of the number of users and per-user bandwidth demand in access networks. The rising demand has given impetus to multiple business partners (BPs) to participate in the business of access networks. However, till date most access networks follow a vertical integration model [1], where a new BP must establish its network and distribution infrastructures before providing services. This in turn requires a significant initial setup cost for the BP. Therefore, every time a customer desires to change BP, it has to pay the infrastructure set-up cost. In addition, the huge "initial setup cost" discourages potential (small) business units from entering the access network as a BP.

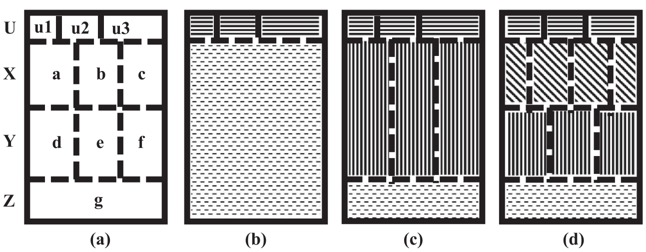

Fig. 1. (a) Vertical segmentation of the telecomm infrastructure; (b), (c) and (d) are the different scenarios of open access. Different layers; U—user, X—SP, Y—NP, Z—PIP.

Open access networks (OANs) provide a potential solution to the "initial setup cost" problem. The available literature on open access architectures [1]–[4] propose partial opening of the optical distribution network (ODN) for sharing by multiple BPs. However, sharing the ODN suffers from physical-layer security vulnerabilities. The OAN scheme proposed in [1] is good on sharing but poor on physical-layer security and passivity (passivity is a desirable feature). The passive optical network (PON) based OAN schemes proposed in [2], [3] have moderate physical-layer security that achieve limited sharing of the ODN between multiple BPs. Thus, there exists a trade-off between sharing the ODN and physical-layer security.

In an open access scenario, the telecom infrastructure can be segmented into multiple layers (U, X, Y, Z in Fig. 1(a)). Multiple BPs of different sizes may co-exist in one or more layers (see Fig. 1(b)–(d)). Fig. 1(b) depicts a scenario with a single BP and multiple users, while multiple BPs at the different layers are present in Fig. 1(c), (d). We next discuss the roles of these BPs depending upon their entry points into the OAN using Fig. 1(a). The description of different BPs is provided in Table I.

- The physical infrastructure provider (PIP) exists at level Z Fig. 1(a)) and provides physical-layer connectivity using duct, trenching, fiber, cable and passive equipment.
- The network provider (NP), at level Y (see Fig. 1(a)), rents the fiber layout from the PIP and owns network equipment for data distribution. It also ensures Internet protocol (IP) services and media access control (MAC).
- The service provider (SP) optionally exists at level X (see Fig. 1(a)), and borrows a segment of the ODN from the PIP and the distribution equipment in the region of service

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TABLE I
OPEN ACCESS: DEFINITION [5], [6]

Terms	Description
Vertical infrastructure owner	Owns the complete access infrastructure, e.g., Tele2, Telenor in sweden
Open access owner	Jointly owned by the PIP, NP and SP, e.g., in Sweden.
Physical infrastructure provider	Owns the network layout and passive equipment, e.g., Stokab in Sweden
Network provider	Owns the active equipment and OLT. Rents fibers, and ports of equipment from the PIP, e.g., OpenNet, Zitius.
Service provider	Provides end-to-end service to the users. Rents bandwidth from the NP, e.g., AllTele, Canal Digital.

from the NP. It provides content and application services to the users.

- The users exist at level U (Fig. 1(a)), and rent services from multiple SPs or NPs.

Fig. 1(b) represents a vertical integration model with a single BP owning the complete infrastructure, while Fig. 1(c) and (d) illustrate typical open access scenarios. Multiple NPs co-exist over a single PIP in Fig. 1(c), while different NPs (SPs) share the business with a single PIP in Fig. 1(d). This represents a three layer open model [7]. The co-operation of these BPs (of different sizes) at multiple entry points of the ODN (Fig. 1(b)–(d)) is required in an open access scenario. A summary of the BPs and the network scenarios is provided in Table I.

A typical PON-based OAN consists of an optical line terminal (OLT), two stages of remote nodes and optical network units (ONUs). The physical infrastructure of the open access ODN (fiber layout) has been proposed to be un-segmented in the literature to ensure a common infrastructure. This encourages fair business competition. In such networks (see Table I), the PIP owns the ODN equipment and the NPs own only the equipment at the OLT [2], [3]. The ONUs are assumed to be owned by the users or in-home NPs. The SPs (if present) rent ports (bandwidth) of the OLT from the NP. In the architecture discussed in this paper, the ownership of the NP, SP and the PIP is according to the above convention. Through a collaboration of these multiple investors, the risk as well as the expenditure involved are divided in the open access scenario. This attracts new market players for investment. Such ODNs must allow the PIP and NP(s) to recover the cost of network installation from multiple SPs, which results in a better business model. The PIP (see Table I) is generally a big market player, such as, the municipality, while the NPs and SPs can be small or big organizations (see Fig. 1(b)–(d)) with entry points in the ODN as discussed earlier. An open access scheme should discourage the monopolies of the existing NPs (SPs). This introduces competition among the NPs (SPs), resulting in potential price reduction and better services. It also results in introduction of newer services and technological innovations in the network.

In this paper we propose a passive, open access architecture with adequate physical-layer security over a shared ODN. The proposed scheme provides cost benefits due to improved sharing of the ODN and ODN-related expenditures (viz., trenching, fiber layout, etc.) between the BPs at multiple distribution levels, compared to the architectures proposed in the literature [1]–[4]. Moreover, the ODN can be shared with different granularities

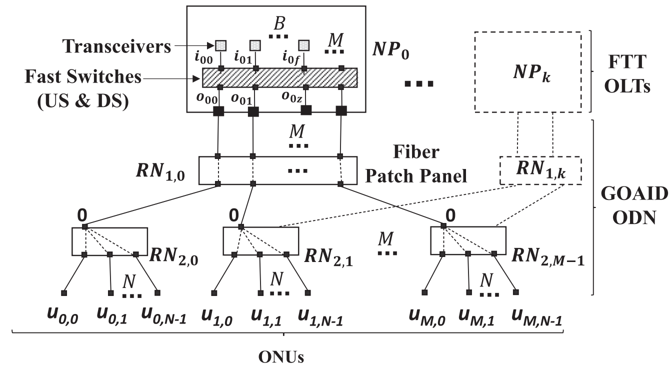


Fig. 2. Proposed architecture of the GOAID-ODN, combined with the FTT OLT ($RN_{2,x}$ employs AWGs).

thereby inviting BPs of different sizes into business. The ODN further supports incremental deployment (ID, scale up in differential granularities) thereby reducing the expenditures during future expansion. Thus in summary, the proposed scheme simultaneously ensures co-existence, penetration, isolation, security and privacy, passivity, incremental deployment and energy efficiency. These features are discussed in the text. To the best of our knowledge, no OAN architectures proposed in literature [1]–[4] ensure all the above features simultaneously.

The rest of the paper is organized as follows. In the next section we discuss the architecture for an open access ODN and a novel OLT architecture for a TWDM scheme. In Section III we illustrate that the proposed ODN ensures all essential and additional features to provide open access. Thereafter, in Section IV we discuss the support for co-existence of some typical OLT schemes over the proposed open access architecture followed by a discussion on some variable parameters in the proposed architecture. Section V presents different types and scenarios of open access. We quantify the important aspect of physical-layer security inherent to the proposed schemes in Section VI, followed by some business case studies. Finally Section VII concludes the paper.

II. NOVEL ARCHITECTURES SUPPORTING OPEN ACCESS

In this section we propose two architectures. An architecture for a green open access ODN with support for incremental deployment (GOAID-ODN) is introduced in Section A, followed by a novel OLT architecture for TWDM PONs (architecture with fast switch and tunable transceivers—FTT) in Section B. The proposed OLT architecture optimally exploits the advantages of GOAID-ODN. The architectures of GOAID-ODN and FTT OLT are illustrated in Fig. 2, and the annotations used are listed in Table II.

A. GOAID-ODN Architecture

The GOAID-ODN, proposed in this section can have multiple NPs working with (i) same or different types of OLTs (e.g., WDM, TWDM etc.) and (ii) different business strategies (e.g., large, small, aggressive in business, etc.). This is termed as *co-existence* and prevents monopoly of NPs (SPs) with any particular technology. Co-existence of NPs with similar OLT schemes has been termed as concurrency in the literature [2].

TABLE II
ANNOTATIONS USED IN THE FIGURES AND TEXT

Symbol	Details	Symbol	Details
B_K	No. of transceivers of NP_k	k	$(k+1)^{\text{th}}$ network provider
N	No. of available wavelengths, No. of $RN_{2,z}$ ports (input/output).	M_k	No. of $RN_{2,z}$ served by NP_k
$RN_{1,k}$	$(k+1)^{\text{th}}$ first stage remote node (connecting to NP_k)	$RN_{2,z}$	$(z+1)^{\text{th}}$ second stage remote node
i_{kf}, o_{kz}	f^{th} fast switch port of NP_k connecting to z^{th} $RN_{2,z}$	$\lambda_i\ \lambda_i'$	Up and downstream wavelengths
d_z	No. of distribution fibers connecting to $RN_{2,z}$	$c_{z,a}^{k,old}$ $c_{z,a}^{k,new}$	Sustainable bit-rate of $u_{z,a}$ before and after expansion
$d_{k,z}$	No. of distribution fibers connecting to $RN_{2,z}$ from NP_k	$u_{z,a}$	a^{th} user of $RN_{2,z}$
δ	Incremental bandwidth demand	$\rho_{a,z}^k$	Indicates if a user is present ($=1$) or not ($=0$)
L	Bit-rate of one laser (10 Gb/s)	G_z^k	Group of users from $RN_{2,z}$ subscribed to NP_k
$c_z^{k,old}$ $c_z^{k,new}$	No. of users in G_z^k before and after expansion	$s_z^{k,old}$ $s_z^{k,new}$	Sustainable bit-rate of G_z^k before and after expansion
$\vert a\vert_z$	No. of users in G_z	n_z^{AWG}	No. of AWGs required at $RN_{2,z}$

GOAID-ODN supports the co-existence of multiple NPs adopting the typical wavelength division multiplexed (WDM) and TWDM OLT schemes. At the same time it can also support NPs adopting the OLT scheme discussed in the Section B. Below we discuss the architectural details of GOAID-ODN.

Architectural details: The GOAID-ODN (illustrated in Fig. 2) implements a fiber patch-panel at each of the first-stage remote-nodes—$RN_{1,k}$. Every $RN_{1,k}$ connects to one or all M second stage remote nodes—($RN_{2,z}$; $z=\{0,\ldots,M_k-1\}$). Each $RN_{2,z}$ has one or more $N\times N$ arrayed waveguide grating (AWG) devices. Distribution fibers, each from the same or a different $RN_{1,k}$ (kth first stage of remote node) connect to the input ports of the $RN_{2,z}$ and facilitate open access. Each $RN_{1,k}$ connects to a different OLT from separate NPs (SPs). The users ($u_{z,a}$; $a=\{0,\ldots,N-1\}$) connect to $RN_{2,z}$ and are equipped with tunable transceivers. The tunable transceivers allow users to change NPs (without modifying the fiber distribution) and solves the inventory problem associated with fixed transceivers.

Advantages Compared to Cascaded AWG With Fast Switch and Tunable Components (CAFT) [8]: The GOAID-ODN (see Fig. 2) retains the advantages of CAFT [8], viz., security, privacy, passivity and excellent reach. It has added flexibility of bandwidth sharing and expansion compared to CAFT. Moreover, the disadvantages of loss-imbalance and imperfect multiplexer periodicity, due to the dispersion-shift problem [12] of cascaded AWGs (present in CAFT [8]) is resolved in GOAID-ODN. This is because GOAID-ODN employs a single stage of AWG (at $RN_{2,z}$). Moreover, the maximum number of users in CAFT [8] is limited to N^2, (for N wavelengths, each for US and DS). However, the maximum number of users supported by GOAID-ODN under NP_k is $N\times M_k$ due to M_k $RN_{2,z}$ and N users per $RN_{2,z}$ (where M_k is independent of N)

$$G_z=\{u_{z,a}\};\ \forall 0\ \leq a<N. \tag{1}$$

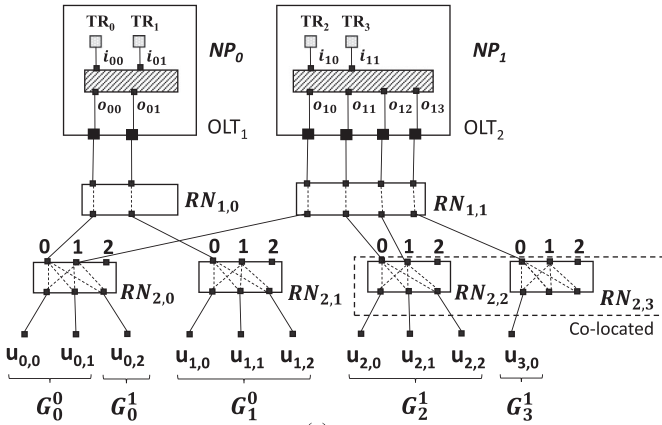
Each output port of the fiber patch-panel is associated with a group of users (1). The presence of a fiber patch-panel at $RN_{1,k}$ (instead of AWG, as in CAFT [8]) changes the grouping of the users from CAFT as well as allows an arbitrary value of M_k independent of N. The number of groups is equal to the number of fiber patch-panel ports (also equal to the number of $RN_{2,z}$).

Physical-Layer Security: The GOAID-ODN has an AWG based distribution, and is supposed to provide adequate physical-layer security. However, there are some associated security issues. The ports of an AWG (used in $RN_{2,z}$; Fig. 2) behave as optical filters. The signal at each port suffers out-of-band crosstalk [15] from the adjacent ports (due to the spreading of the incident beams) of the AWG. Upstream (US) data of a user can be corrupted by malicious users by crosstalk attacks (high signal powers in the adjacent ports increase the crosstalk). This security threat can be more serious for a long reach PON where users are diversely located across a large distance. In such scenarios, the received power from different users varies widely. This provides incentive to malicious users located nearer to the OLT to launch high power and hamper the transmission of a distantly-located user. We note that the users have a common path (distance) between the $RN_{1,k}$ and the OLT. Thus the differential distance between the users is in the last mile. In Section V, we provide a quantitative analysis and prove that GOAID-ODN has adequate security over crosstalk attacks.

B. Fast Switch With Tunable Transceivers (FTT): A Novel OLT Architecture for TWDM PONs

We discuss an OLT architecture for TWDM-PONs (called Fast switch with Tunable Transceivers—FTT) in this section using Fig. 2. The scheme is analogous to the OLT architecture proposed by us in CAFT [8], however with better expansion possibilities. The design of the FTT OLT for NP_k incorporates B_k tunable lasers and B_k tunable receivers, each followed by a $M_k\times M_k$ fast switch ($B_k\leq M_k$) for US and downstream (DS), respectively. SOA based fast switches are used in the FTT OLT to switch the lasers to different ports of the fiber patch-panel. The fast switch can connect any transceiver to any $RN_{2,z}$ with port mappings ($i_{kf}\rightarrow o_{kz}$, fth transceiver of NP_k connects to $RN_{2,z}$).

Advantages Over CAFT OLT: The CAFT OLT can share a maximum bandwidth of L among the users of a particular $RN_{2,z}$. The FTT OLT has a better flexibility in this regard compared to CAFT [8]. It can share any bandwidth less than $d_z\times L$ ($d_z\leq N$) among the users of a particular group (G_z). Thus, a maximum per-user bandwidth of L can be provided



(a)

		$u_{0,0}$	$u_{0,1}$	$u_{0,2}$	$u_{1,0}$	$u_{1,1}$	$u_{1,2}$	$u_{2,0}$	$u_{2,1}$	$u_{2,2}$	$u_{3,0}$
NP_0	DS :	λ_0	λ_1	λ_2	λ_0	λ_1	λ_2	–	–	–	–
	US :	λ'_0	λ'_1	λ'_2	λ'_0	λ'_1	λ'_2	–	–	–	–
NP_1	DS :	λ_1	λ_2	λ_0	–	–	–	λ_0	λ_1	λ_0	λ_0
	US :	λ'_1	λ'_2	λ'_0	–	–	–	λ'_0	λ'_1	λ'_0	λ'_0

(b)

Fig. 3. (a) Co-existence of TWDM NPs implementing FTT in the GOAID-ODN (b) Wavelength mapping for the NPs to access users (FS—Fast Switch, TR—Tunable Receivers).

by the FTT OLT. Depending on the requirements, transceivers and fast switch modules can be installed (increase B_k and M_k respectively) enabling the FTT OLT to expand.

III. Open Access Features Supported by GOAID-ODN

In this section, we illustrate the parallel operation of two NPs adopting the FTT schemes over a common GOAID-ODN. We also state some essential and desirable features of OANs (with the help of Fig. 3) and illustrate that the operation of FTT over GOAID-ODN satisfies each of them. GOAID-ODN also ensures similar features for NPs adopting other OLT schemes.

In the example of Fig. 3, two NPs adopting the FTT OLT scheme (NP_0, NP_1) have been assumed, with $N = 3, M_0 = 2, B = 2$ for NP_0 and $N = 3, M_1 = 4, B = 2$ for NP_1. NP_0 and NP_1 connect to the regions served by $\{RN_{2,0},\ RN_{2,1}\}$ and $\{RN_{2,0},\ RN_{2,2},\ RN_{2,3}\}$, respectively. NP_1 connects to $RN_{2,2}$ using two distribution fibers, in order to increase the total bandwidth reaching $RN_{2,2}$. $u_{2,2}$ connects to the second distribution fiber of $RN_{2,2}$, and therefore communicates with NP_1 on λ_0, λ'_0 for DS, US respectively ($m = 1, j = 2$ in (2)). The set of tunable receivers (TR_r) in Fig. 3 consists of a tunable filter followed by a broadband photo-detector. The group G_z under NP_k is denoted by G_z^k (see Fig. 3(a)).

A. Essential Features

The essential features of OANs are discussed below for FTT over GOAID-ODN.

1) Co-Existence and Penetration: GOAID-ODN supports co-existence of multiple NPs as illustrated in Fig. 3 where two NPs adopt the FTT OLT scheme. There can be a maximum of N NPs per $RN_{2,z}$ (N port AWG at $RN_{2,z}$; $2N$ available wavelengths). The wavelength routing property of the AWGs (2) assumes that, the output is received from port m if λ_i is incident on port j of the AWG. Symmetric AWGs have been used to simplify the US and DS mapping. Thus, for the user $u_{z,a}$, the US wavelength (λ'_i) of NP_k $(0 \leq k < N)$ is given by the solution to (3) (assuming NP_k connects to input port k of $RN_{2,z}$). The DS wavelength (λ_i) follows a similar routing as λ_i, λ'_i are separated by a free spectral range of the AWGs (symmetric type).

$$m = (N - j + i) \, mod \, N \quad (\forall 0 \leq i < N, 0 \leq j < N) \quad (2)$$

$$i = (m + k) \, mod \, N \quad (0 \leq b < N). \quad (3)$$

The US and DS wavelengths required to serve the users have been illustrated in Fig. 3(b) for the (sample) network connection shown in Fig. 3(a). It is observed that users under a particular $RN_{2,z}$ can be reached by all NPs connecting to that $RN_{2,z}$. However, the wavelength(s) for connecting to different NPs are unique. Thus, if a user desires to change NP, no change in the infrastructure is required. The other NP requires to tune any particular laser to the user's wavelength to be able to reach it. For example, if $u_{0,0}$ is subscribed to NP_0 and desires service from NP_1, no architectural modification is required. The transceiver with $u_{0,0}$ is required to be tuned to (λ_1, λ'_1) from (λ_0, λ'_0) for DS (see Fig. 3(b)). This ensures *co-existence* of multiple NPs in GOAID-ODN and increases the wavelength reusability. It also reduces the initial set up cost and cost for future expansion. Moreover, a user may wish to rent simultaneous service from multiple NPs in which case, it must be equipped with multiple transceivers for communicating with the respective NPs.

It is to be noted that the $N \times N$ AWG multiplexer (used at $RN_{2,z}$) suffers from the imperfect multiplexer periodicity due to waveguide dispersion [12]. As such, there is a difference in frequency between the λ_i, λ'_i used by NP_0 and NP_1 (see Fig. 3(a)). This is because, the incident ports (at $RN_{2,z}$) are different for each NP. To overcome this problem, the user needs to be informed about the exact transmission frequency during NP switching. However, analysis of the imperfect multiplexer periodicity is beyond the scope of the present paper.

Penetration implies that, an NP (SP) can serve a user located anywhere in its regions of interest (inside the OAN). The NPs (SPs) are able to reach all the users in their regions of service, in GOAID-ODN, by changing the wavelengths. For example, in Fig. 3 NP_0 can reach all users under $RN_{2,0}$and $RN_{2,1}$ (and choose not to connect to $RN_{2,2}$). Thus GOAID-ODN facilitates *penetration*.

2) Isolation: Isolation requires an NP (SP) and its users to be secured from unwanted behavior of the users under other NPs (SPs) (preferably physical-layer isolation). Isolation associated with GOAID-ODN is explained with the illustration of Fig. 3. Suppose $u_{0,0}$ and $u_{0,1}$ are subscribed to NP_0, $u_{0,2}$ is subscribed to NP_1 and $u_{0,0}$ is a malicious user. User $u_{0,0}$ needs to tune to λ'_1 (maliciously) to reach NP_1. However, NP_1 transmits only on (λ_0, λ'_0) for G_0^1 (i.e., on o_{00}, Fig. 3(a)) to connect to $u_{0,2}$. As such, $u_{0,0}$ cannot receive or hamper transmission of NP_1. This preserves *isolation* (inter-NP sanctity) in the GOAID-ODN.

B. Additional Features

Below we discuss some desirable features of OANs.

1) Security and Privacy: Security [8] implies protection of a subscriber's US data from malicious behavior by subscribers of the same NP (SP). Continuing with the example of Fig. 3, according to the wavelength mapping (see Fig. 3(b)), $u_{0,0}$ can:

i. keep its transmitter tuned to λ'_0 all the time

ii. maliciously tune to λ'_1 or λ'_2.

We next analyze and quantify the security provided by the GOAID-ODN in both the above cases.

The receiver (say TR_0 in Fig. 3(a)) at the OLT will be tuned to λ'_0 and the FS configuration will be connected as ($o'_{00} \rightarrow i'_{00}$) only when the OLT is required to connect to $u_{0,0}$. At other times either the receiver is tuned to a different wavelength (e.g., λ'_1 to connect to $u_{0,1}$) or the FS connects the receiver to a different port (e.g., $o'_{01} \rightarrow i'_{00}$ to reach G_0^1). Thus $u_{0,0}$ cannot hamper the receivers at the OLT by tuning to λ'_0 due to the unique combination of switch configuration and wavelength selection that is assigned to each user.

If $u_{0,0}$ tunes to λ'_1 it reaches a different NP and cannot disturb its respective NP (cf. discussion on *Isolation*). On the other hand if $u_{0,0}$ tunes to λ'_2, the transmission is rejected from an empty port of the AWG (due to its routing property; (2)). Thus, security is ensured by the GOAID-ODN.

Privacy refers to the protection of DS data from access by the subscribers of the same NP (SP) [4]. User $u_{0,0}$ can receive transmission only on λ_0 and λ_1 but not on λ_2 due to the wavelength routing property of $RN_{2,z}$. $u_{0,0}$ receives transmission only on λ_0 from NP_0. No transmission is received by $u_{0,0}$ on λ_1, as it is not subscribed to NP_1. Thus, GOAID-ODN ensures privacy of users, providing features similar to WDM. However, sharing by fast switch makes it TWDM.

2) Passivity: Passivity implies the absence of any active element in the ODN, thereby minimizing OpEx and ensuring higher availability. The GOAID-ODN is comprised of passive elements like fiber patch-panel, circulators and AWGs.

3) ID and Green Technology: Incremental deployability of the ODN reduces the cost of expansion. When the demand increases, the NP (SP) can incrementally scale up (ID) its infrastructure on a need basis through incremental expenditures. The flexibility of GOAID-ODN ensures this and results in a smaller initial set-up cost for the NPs (SPs) which is particularly suitable for small NPs (SPs). Thus, if NP_1 desires to serve only $u_{0,2}$, it is required to rent one of each of the following; last mile fiber, distribution fiber (which are already laid by the PIP during network installation), input and output ports of $RN_{2,z}$ and $RN_{1,k}$. The bigger NPs can expand in the GOAID-ODN by installing more transceivers at the OLT and increasing the fiber patch-panel port count (both contribute to increase B_k, and if required M_k). Therefore, to reach users of G_1^0, NP_0 (assumed, big NP) is required to rent new feeder, distribution and last mile fibers and ports of $RN_{2,1}$ from the PIP. Thus, GOAID-ODN allows the NPs to operate with optimal number of transceivers due to the inherent flexibility of bandwidth sharing. Since at low network loads, the network operation in FTT over GOAID-ODN is optimally managed using a few transceivers, the scheme provides a green solution.

Some of the popular open access architectures have been reviewed by the authors of [3]. The AWG based architectures (in [3]) ensure the desirable features of isolation, co-existence and penetration. There are two types of AWG based ODNs defined in the literature [3], [10]; one has AWG at both stages of remote nodes while the other has an AWG at the first stage of remote node followed by a power splitter in the second stage remote node. The cascaded AWG based architectures ensure security and privacy but suffer from the loss-imbalance problem [12]. Moreover, the flexibility of bandwidth sharing is also absent in these architectures which reserve particular wavelengths for different users. The architectures having AWG and power splitter at the two stages of remote nodes lack from security due to the collision domain in the power splitter. Thus a tradeoff between security and flexibility of bandwidth sharing is observed in the PON architectures proposed in the literature. The FTT over GOAID-ODN retains the flexibility of bandwidth sharing (including support for bit-stream open access) and simultaneously guarantees the essential and desirable features of open access (discussed above). The flexibility of bandwidth sharing inherent to FTT over GOAID-ODN allows for ID which is essential for energy efficiency. Thus GOAID-ODN stands out from the open access schemes proposed in the literature [3] in multiple aspects.

C. ID Planning (Expansion)

The kth NP (SP) may desire to expand its user base ($c_z^{k,old} < c_z^{k,new}$, $S3$ in Fig. 4) or be required to increase the per-user bandwidth (total extra bandwidth demand—δ). We denote the sustainable bandwidth (the average bandwidth promised to the users) of $u_{z,a}$ by $s_{z,a}^{k,old}$. If $u_{z,a}$ is currently subscribed to NP_k or SP_k, then $\rho_{a,z}^k = 1$ otherwise 0. We also assume that the extra bandwidth demand is from G_z^k. $s_z^{k,old}$ and $s_z^{k,new}$ represent the original and new bandwidth demands from G_z^k respectively. The demand $s_z^{k,old}$ (4) from G_z^k results from $c_z^{k,old}$ users due to their previous bandwidth demands ($s_{z,a}^{k,old}$). The new bandwidth demands ($s_z^{k,new}$) arises from the new user base in G_z^k ($c_z^{k,new-1}$) which is a δ change from $s_z^{k,old}$ (5).

$$s_z^{k,old} = \sum_{a=0}^{c_z^{k,old}-1} s_{z,a}^{k,old} \times \rho_{a,z}^k \tag{4}$$

$$s_z^{k,new} = s_z^{k,old} + \delta = \sum_{a=0}^{c_z^{k,new}-1} s_{z,a}^{k,new} \times \rho_{a,z}^k. \tag{5}$$

The flowchart for the expansion planning algorithm is provided in Fig. 4. Some of the assumptions for the expansion algorithm given in Fig. 4 are discussed below:

a) The number of input ports (B_k) of the FS (NP_k) is related to the number of output ports (M_k) by $B_k \leq M_k$.

b) The overall bandwidth of $RN_{2,z}$ is limited by the number of distribution fibers reaching it and the bandwidth available from the OLT. The maximum bandwidth provided by NP_k at $RN_{2,z}$ is limited by $\min(d_{k,z}, B_k) \times L$. The number of subscribers ($\sum_k c_z^{k,new}$) and the

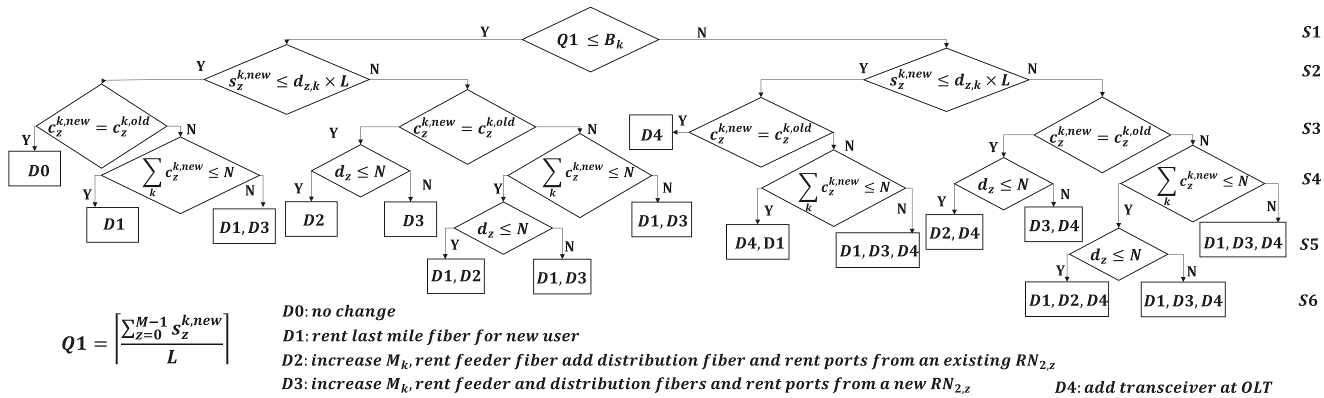


Fig. 4. Flowchart for the expansion planning algorithm (L—per laser bandwidth, N—No of available wavelengths, B—No. of transceivers at the OLT).

distribution fibers connecting to $RN_{2,z}$ is limited by its input and output ports.

c) An NP (SP) pays the PIP for each of the ONUs and the number of $RN_{1,k}$ ports rented. Each $RN_{1,k}$ port corresponds to a $RN_{2,z}$ input port, a distribution fiber and a feeder fiber while each ONU requires a $RN_{2,z}$ output port and a last mile fiber.

Below we discuss the different check conditions in Fig. 4.

- $S1$: NP_k decides if the overall bandwidth demand $\left(\sum_{z=0}^{M-1} s_z^{k,new}\right)$ can be supported by the B_k transceivers (each supports L bps) at its OLT.
- $S2$: NP_k decides if the new bandwidth demand from a particular $RN_{2,z}$ $\left(s_z^{k,new}\right)$ can be supported by the $d_{z,k}$ distribution fibers (each supports L bps) rented for that $RN_{2,z}$.
- $S3$: NP_k decides if there is an increase in the number of customers for a particular $RN_{2,z}$ $\left(c_z^{k,new} = c_z^{k,old}\right)$.
- $S4$: PIP decides if the required number of input ($d_z = \sum_k d_{z,k}$) and output ($\sum_k c_z^{k,new}$) ports of a $RN_{2,z}$ exceeds N.
- $S5$: PIP checks if a new $RN_{2,z}$ is to be installed ($d_z \leq N$).

The expansion planning algorithm is triggered by a change in the bandwidth demand. The new demand can arise from the existing users or due to an increase in the number of users. The condition $Q1$ is triggered ($S1$) if the new demand surpasses the bandwidth supported by an NP in the last mile group. The new resources required to support expansion ($D0 \ldots D5$) are calculated in a hierarchical way at different stages ($S_1 - S_6$). Thus in GOAID-ODN, the SPs demand the required bandwidth from the NP. The NP installs the required resources and rents infrastructure from the PIP. The expansion undertaken by NP_k does not affect other NPs as GOAID-ODN ensures isolation.

Moreover, if an NP requires to connect to a new $RN_{2,z}$ or to a $RN_{2,z}$ with no vacant ports, it pays the same rent as that of any other port. This is unlike in a typical OAN where the NP needs to install new infrastructure for any new target region. In GOAID-ODN, the NP does not have knowledge of the network layout or user distribution across the network. The PIP installs remote nodes and fibers time to time depending on the business scenarios in different regions as per the requirements of all NPs. In GOAID-ODN, the OpEx for patching is covered by the PIP, and is much less as NP change does not require re-patching.

The number of transceivers B_k required at the OLT is given by (6), the number of $RN_{2,z}$ output ports ($|a|_z$) by (7), d_z by (8), and the number of AWGs in a region (n_z^{AWG}) by (9).

$$B_k = \frac{\sum_{z=0}^{M-1} s_z^{k,new}}{L} \tag{6}$$

$$|a|_z = \sum_k \sum_a \rho_{a,z}^k \tag{7}$$

$$d_z = \sum_k \frac{s_z^{k,new}}{L} \tag{8}$$

$$n_z^{AWG} = \left(\sum_k \frac{|a|_z}{N}\right). \tag{9}$$

B_k is derived from the total bandwidth demand of users under an NP (SP). Since complete flexibility of bandwidth-sharing is present in FTT over GOAID-ODN, the total bandwidth can be shared among all users of the NP. The number of required $RN_{2,z}$ output ports ($|a|_z$) depends on the number of users of all service providers existing in that region. The required number of distribution fibers ($RN_{2,z}$ input ports) depends on the bandwidth demand of all NPs ($\sum_k s_z^{k,new}/L$) connecting to a $RN_{2,z}$. Moreover, the number of AWGs required at a $RN_{2,z}$ depends on the number of users present in that region (a user cannot demand the bandwidth $> L$ as a single fiber reaches it).

The expansion algorithm calculates the optimal d_z and B_k required, given the bandwidth demands of the users. These are the minimal values that can be achieved under the restriction that users cannot be shifted from their respective $RN_{2,z}$ to provide free bandwidth to demanding users. The optimal values are exclusive to FTT over GOAID-ODN and result from the flexibility of bandwidth sharing. Due to the modular approach of the expansion algorithm, different NP_k can independently calculate the required resources without any message exchange. This reduces the complexity of deciding the optimal resources to be rented. The GOAID-ODN also eliminates the need and

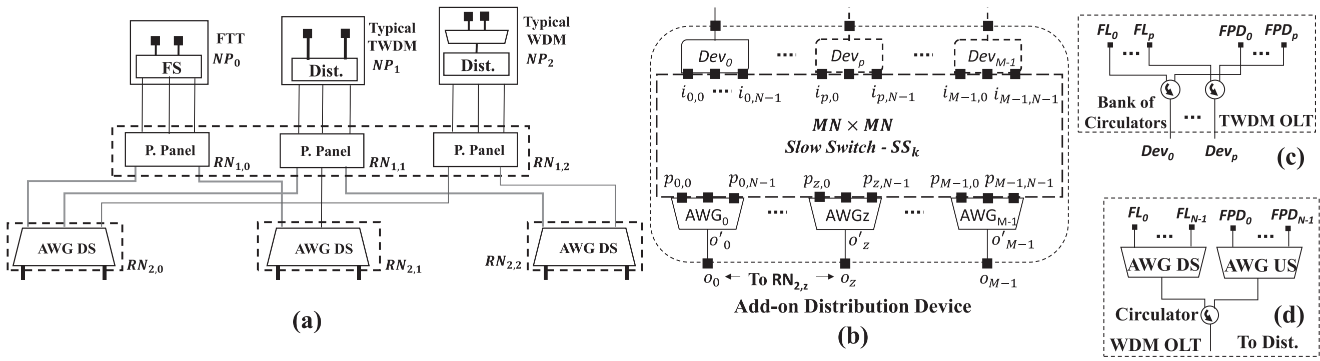


Fig. 5. (a) Co-existence of FTT and typical TWDM NPs over the GOAID-ODN (b) Distribution device (add-on) for a typical TWDM OLT (c) Architecture of the a typical TWDM OLT (FL –Fixed Laser, FPD – Fixed photo detector) (d) Architecture of a typical WDM OLT.

complexity of installing the network elements by the NPs unlike in conventional open access architectures [3].

Thus GOAID-ODN is a highly flexible scheme supporting ID, which allows slow investment for gradual expansion of the physical infrastructure. The FTT over GOAID-ODN can typically support a large number of users over a single OLT. It also allows controlled increase of power consumption. This makes the GOAID-ODN a green technology with ID support. The advantage of ID in GOAID-ODN will be quantified in Section VI-B from the perspective of power and per-user cost.

IV. Co-Existence Supported by GOAID-ODN

Some existing BPs operating with typical TWDM or WDM schemes (non-open access) may decide to expand by joining the GOAID-ODN (due to its explicit cost benefits). This provides incentive for co-existence to NPs (SPs) with typical OLT schemes over the GOAID-ODN, which has been discussed in this section. Over time, the NPs with typical TWDM or WDM OLTs may completely migrate to FTT over GOAID-ODN. In Fig. 5(a) the *co-existence* of three NPs implementing FTT and the typical TWDM and WDM OLTs over the GOAID-ODN has been shown. NP_0 operates with the FTT OLT, NP_1 with a typical TWDM OLT [11] and NP_2 with a typical WDM OLT.

A. Co-Existence of TWDM NPs (FTT With Typical TWDM)

In this section, we discuss the integration of a typical TWDM NP (NP_1) into the GOAID-ODN (see Fig. 5(a)). The OLT of NP_1 (see Fig. 5(c)) is expected to have fixed transceivers [11] that are scheduled by a common MAC. The ODN is similar to that of Fig. 3(a) (unlike the ODNs of typical TWDM schemes that employ a passive power splitter (PS) followed by an AWG [10]). To integrate the typical TWDM scheme in the GOAID-ODN an add-on device is required to be connected to the OLT. This device is illustrated in Fig. 5(b) and is discussed below.

Integration into GOAID-ODN: The add-on distribution device (see Fig. 5(b)) performs the routing for the typical TWDM scheme when integrated into the GOAID-ODN. It comprises of M Dev_p $\{p = 0, 1, 2 \ldots M-1\}$, an inexpensive switch to maintain connectivity and M AWG_zs $(z = 0 \ldots M-1)$. The Dev_p in Fig. 5(b) are $1 \times N$ PSs. Each Dev_p (PS) connects to a transceiver pair (at OLT) at one end and a $(M * N) \times (M * N)$ fiber patch-panel or an inexpensive (slow) switch—SS_k at the other end. Thus M transceivers are required at the OLT to serve $(M * N)$ users. The output ports $(p_0 \ldots p_{N-1})$ of SS_k are grouped (in groups of N) under the M AWG_zs that multiplex the different wavelengths from multiple Dev_p to a single distribution fiber.

Working of the Add-On Device: The Dev_p (PS) shares the corresponding transceiver pair among the N input ports $(i_{p,0} \ldots i_{p,N-1})$ of SS_k. The SS_k connects each input port to a corresponding output port thereby sharing the transceiver pair among N users. SS_k can be configured to dynamically add/ remove end users according to their choice of NP. Thus, SS_k can be an inexpensive (slow) opto-mechanical switch. Each output port of SS_k connects to a subscriber. SS_k also facilitates inter-NP isolation and data security (discussed later). The following example explains the connectivity and the wavelengths required for NPs to connect to GOAID-ODN using the add-on device. To reach user $u_{1,2}$ (see Fig. 3), NP_1 is required to install or tune a transceiver to λ_0 which is connected through an unused Dev_p to an output port $p_{1,0}$ by SS_k.

Aspects of Open Access: The valid subscribers are connected to the NP_k due to the port connection (input-output) of SS_k. The malicious (or unwanted) users cannot reach other NPs by any means. The users connecting to a particular Dev_p are served by the same transceiver at the OLT. These users define the group G_p^k for the typical TWDM and WDM schemes. Also, users of a particular group are protected from the users of another group due to different PS (Dev_p) and hence the respective transceivers. This provides inter-group (G_p^k) security like any typical TWDM scheme. The architecture retains *passivity* (SS_k is a user connectivity device and not a routing switch). The wavelength mapping for the users is given by (3), thereby ensuring co-existence. *Penetration* is ensured by installing the required transceivers (at the OLT) and configuring the input-output port mapping of SS_k for connecting to valid subscribers.

Unlike in FTT, the transceivers in the typical TWDM OLT cannot serve users of other groups (in the absence of the fast switch at the OLT). This limits the flexibility of bandwidth sharing in a typical TWDM scheme. Moreover, a cascaded AWG configuration takes place due to the multiple stages of the AWGs (one in the $RN_{2,z}$ and another in the add-on device) involved in the TWDM over GOAID-ODN (also true for the WDM over GOAID-ODN discussed in Section B). This may result in the dispersion-shift problem of cascaded AWGs which can be avoided by substituting the AWGs in the add-on device with dielectric thin filters (DTF). However, the analysis of this problem is beyond the scope of the present paper.

B. Co-Existence of a Typical WDM NP With a TWDM (FTT) NP

In this section, we discuss the co-existence of an NP adopting a typical WDM scheme over the GOAID-ODN [13] (NP_2 in Fig. 5(a)). The WDM OLT (see Fig. 5(d)) scheme implements dedicated (fixed) transceiver for each user. As such, the WDM NP can serve a maximum of M users.

1) Integration Into GOAID-ODN: For the typical WDM scheme, the Dev_ps are $1 \times N$ AWGs (AWG_p for convenience). The AWG_ps de-multiplex the wavelength channels (from the OLT) into separate input ports of SS_k in accordance to (3). SS_k routes the channels to the AWG_zs connected to the output port of SS_k ($p_{z,0} \ldots p_{z,N-1}$), which in turn connect to the respective $RN_{2,z}$. To reach any user, the wavelength required to connect is given by the PIP to the NP. The NP installs the required transceiver pair and configures the SS_k to establish the essential input-output ($AWG_p - AWG_z$) port mapping. Since there can be $M \times N$ users in the network, the add-on distribution device has a provision for M AWG_zs (and hence M OLTs).

2) Security, Privacy and Isolation: The WDM OLT provides complete data security and privacy. The add-on device does not include any splitter device (broadcast devices for bit-stream multiplexing). This ensures security and privacy to the ONUs and isolates an NP and its subscribers from subscribers of other NPs. The aspects of open access like co-existence and penetration is similar to the previously discussed schemes.

C. Co-Existence of TDM Scheme With FTT OLT

The typical TDM ODN implements a cascaded PS which makes it vulnerable to data privacy and security. This violates the aspect of isolation in open access scenarios. Thus, we do not discuss co-existence of TDM scheme in GOAID-ODN.

1) Comparison of FTT Over GOAID-ODN With Typical OLT: A number of parameters can be varied in the GOAID-ODN according to the NP_k's requirements which adds to its flexibility. The number of subscribers can be varied by simultaneously increasing the number of fiber patch-panel ports (M_k) and z (by installing $RN_{2,z}$). For the typical WDM scheme, more transceivers (user dedicated) are required to be installed. There is limited scope for energy efficiency for typical OLT schemes in GOAID-ODN (unlike FTT over GOAID-ODN) due to their limitation in bandwidth sharing. As such, the energy efficiency varies from limited (typical TWDM) to none (for WDM). This is similar to the typical OLTs which are deployed with their usual ODNs. For NPs with typical OLT schemes over GOAID-ODN, ID is supported anyway.

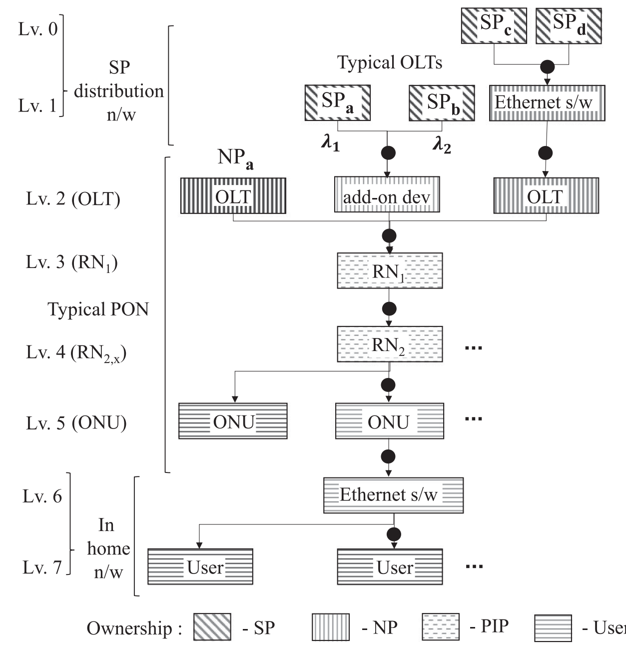


Fig. 6. Schematic of a typical OAN scenario over a PON (Lv. - Level).

In the FTT OLT, a change in M_k effects a change in the number of FS ports (at the OLT). For the typical TWDM or WDM NPs a change in M_k requires an expansion of the add-on device (see Fig. 5(b)). A dedicated Dev_p is required per transceiver in the TWDM scenario while a separate $Dev_p$is required per WDM OLT (transceivers of N different wavelengths).

The number of WDM or TWDM NPs coexisting at a particular $RN_{2,z}$is a function of the number of input ports of the AWGs (at $RN_{2,z}$). This is limited by the number of AWGs installed at that $RN_{2,z}$. Since multiple $RN_{2,z}$ can be installed, many WDM or TWDM NPs can coexist in GOAID-ODN.

V. Open Access Types and Scenarios

In this section, we discuss the possible types and scenarios of open access in GOAID-ODN that ensure co-existence of BPs.

A. Possible Types of Open Access

In literature, open access architectures have been classified into different types, according to the entry point of BPs in the ODN. We next discuss these with reference to GOAID-ODN using Fig. 6. The illustration includes an in-home network and an SP distribution network over a typical PON schematic. It is evident from earlier discussions (see Fig. 3 and Section III) that;

- Each transceiver (at FTT OLT) requires a FS input port.
- Each output port of the FS is associated with a feeder fiber and a $RN_{2,z}$ input port.
- Each $RN_{2,z}$ input port serves to a group of users (G_z^k).
- Each $RN_{2,z}$ output port corresponds to one last mile fiber and connects to a single ONU.

The levels ($Lv_0 - Lv_7$) in Fig. 6 refer to the network equipment at different levels of hierarchy. Depending on the granularity with which the ODN is opened for the SP or the NP at different entry points, the schemes are classified as fiber, wavelength and bit-stream open access [1].

- In fiber-based open access (e.g., NP_a in Fig. 6) the PIP owns the equipment at remote nodes, while NPs (at $Lv_2 - Lv_3$ interface) own the OLT and unbundling equipment for an SP distribution network (if present).
- In wavelength-based open access, SPs rent complete wavelengths (e.g.,SP_a, SP_b in Fig. 6) from the NP. This is possible only for typical WDM and TWDM OLT over GOAID-ODN using the add-on device. In this scenario, wavelength unbundling takes place between Lv_1 and Lv_2 (by the add-on device). The flexibility of wavelength sharing disables wavelength-based open access in FTT.
- Bit-stream open access, involves time sharing of wavelength(s) (e.g., SP_c, SP_d in Fig. 6). This requires sharing the OLT using a layer 2 switch owned by the NP. In these scenario unbundling occurs at $Lv_0 - Lv_1$ interface.

GOAID-ODN supports fiber-based open access between the OLT and $RN_{1,k}$, and wavelength-based open access between $RN_{2,z}$ and the users. Bit-stream open access is supported at the OLT due to the flexibility of bandwidth sharing in GOAID-ODN. In addition, wavelength based open access is provided to the NPs with typical OLT schemes through the add-on distribution device (see Fig. 5(b)). An end-to-end fiber based open access achieves complete physical-layer security as the users are separated at the fiber level. However, the fibers are user-dedicated and hence partially utilized. On the contrary bit-stream open access results in a better utilization of wavelengths at the cost of security concerns. Wavelength based open access provides intermediate utilization as well as security. The architectures proposed in literature ([1], [2], [10]) ensures only one of the above types as they suffer from a trade-off between physical-layer security and flexibility of bandwidth sharing. *GOAID-ODN achieves an appreciable utilization of the ODN due to the sharing of the ODN at all the three granularities and is the first architecture of its kind to do so over a passive ODN with adequate physical-layer security (quantified in Section V).*

The PIP owns the distribution network including the fiber (in between OLT-$RN_{1,k}$, $RN_{1,k}$-$RN_{2,z}$, $RN_{2,z}$-ONU) and the passive ODN equipment. The users exist at Lv_5 or Lv_7 (see Fig. 6); depending upon the presence of an in-home network and bandwidth requirements. The SPs (if SP distribution network is present) operate at Lv_0 or Lv_1. The SPs inform their respective NPs about the bandwidth, user or location requirements. From this information, the NPs calculate the number of transceivers to be installed. The SPs rent bandwidth from the NPs while the NPs rents $RN_{1,k}$ and $RN_{2,z}$ ports (one for every G_z^k or G_p^k accessed) from the PIP. The rent for the ports also includes the rent of the used feeder, distribution and last mile fibers.

B. Possible Scenarios of Open Access in GOAID-ODN

In this section, we discuss some open access scenarios which determine the co-existence of multiple BPs (PIP, SP and NP) at different levels of GOAID-ODN. For open access scenarios, we consider the typical PON schematic depicted in Fig. 6. There can be two levels of open access; between the PIP and the NP at the $Lv_2 - Lv_3$ interface, or between the NP and the SP at the $Lv_1 - Lv_2$ interface if an SP distribution network is present and otherwise at the $Lv_0 - Lv_1$ interface. The open access scenarios relevant to GOAID-ODN are discussed below with reference to Fig. 3 and illustrated in Fig. 1(b), (c) and (d).

i) Fig. 1(b) depicts a traditional vertically integrated operator (no open access) which owns the complete infrastructure.

ii) There can co-exist a single PIP, and multiple NPs (see Fig. 1(c)). The PIP owns the fiber distribution network and the passive equipment at the remote nodes. NPs own respective OLTs and pay to the PIP for the ODN fibers, $RN_{1,k}$ and $RN_{2,z}$ ports. Only fiber-based open access is possible here as multiple NPs rent feeder fibers from the PIP. The users (as per service contracts) can rent services from multiple NPs.

iii) In the best sharing case of open access (see Fig. 1(d)) there can exist multiple NPs or small SPs (horizontally separated). The SPs (if present) adopt bit-stream or wavelength based open access, depending on their OLT architecture and can rent bandwidth from one or more NPs. The ownership of the PIP and the NP is similar, as in the previous scenarios.

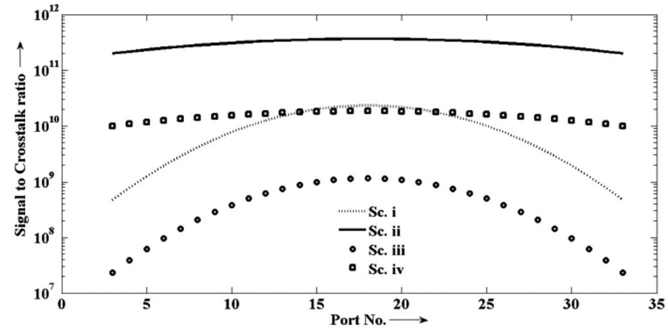


Fig. 7. Plot for signal to crosstalk ratio for the four scenarios listed above.

VI. Network Security and Business Perspective

A. Analysis of Physical-Layer Security

Although the proposed GOAID-ODN architecture ensures typical WDM-enabled physical-layer security, it may however be breached by malicious end-users by resorting to high power transmission from lasers. We provide a quantitative analysis of this physical-layer security issue inherent to the implementation of FTT over GOAID-ODN in this section. We use the assumptions of [16] and the methodology of [16] to analyze the signal to crosstalk ratio which reflects the security in Fig. 7. The length of the feeder is considered to be 10 km (path loss of 0.34 dB/km) and the maximum distance of the user from $RN_{1,k}$ is 35 km (assuming a long reach PON of 45 km span). The insertion loss of the AWG is 4 dB [17]. The design parameters for the AWG has been taken from [15], [16] and [18]. We assume that, the signal is received at any port i (power P_i). Then the out-of-band crosstalk will be observed from ports $i-1$ and $i+1$ of the AWG (due to powers P_{i-1} and P_{i+1}). The equation for crosstalk in the ith port has been derived by the authors of [18] and is therefore not discussed here. Four sets of data ($Sc.i - Sc.iv$, given below) have been plotted for the following scenarios with waveguide spacing as 25 μm and width w;

Sc.i. $P_i = 0$ dBm; $P_{i+1} = P_{i-1} = 0$ dBm; $w = 10\ \mu$m
Sc.ii. $P_i = 0$ dBm; $P_{i+1} = P_{i-1} = 0$ dBm; $w = 4\ \mu$m
Sc.iii. $P_i = -3$ dBm; $P_{i+1} = P_{i-1} = 10$ dBm; $w = 10\ \mu$m
Sc.iv. $P_i = -3$ dBm; $P_{i+1} = P_{i-1} = 10$ dBm; $w = 4\ \mu$m.

For a smaller P_i (-3 dBm), a lower signal-to-crosstalk ratio is observed (see Fig. 7) compared to a higher value of P_i (0dBm). Since the signal to crosstalk ratio is lower at the extreme ports, an optimal design would be to use higher laser powers at these ports and lower powers for the central ports. The ratio also drops for a wider channel waveguide (higher w). From Fig. 7 we observe that GOAID-ODN provides an acceptable P_i/P_{xt} of 10^9 and hence adequate security.

B. Business Perspective

In the following text we illustrate that GOAID-ODN ensures co-existence by mitigating monopoly and encourages a competitive market scenario. We also illustrate that GOAID-ODN provides a green open access solution. Below, we define few parameters that aid us to discuss the business insights.

i) *Subscriber gain rate*—The percentage of subscribers that annually switch to a particular NP to the total number of subscribers existing in the market scenario. This parameter weights the performance of an NP in a competitive market. For example, consider that an NP has 100 users while there are 1000 users in the complete OAN. If 10 users from other NPs switch to this NP, while 20 of its users leave to join other NPs annually, then the subscriber gain rate of that NP is -1%. Thus subscriber gain rate is an indication of the business strategy of an NP (SP) (dormant, aggressive, etc.) in an open access scenario. Higher subscriber gain rates mean a more aggressive NP (SP).

ii) *Growth rate*—The number of fresh users annually joining an NP, expressed as a percentage of its existing subscribers. It is expected that an NP providing good service will attract more fresh subscribers (higher growth rate) as well as existing subscriber from other NPs (higher subscriber gain rate).

iii) *Utilization ratio*—Ratio of the operational (actually used) bandwidth to the maximum supportable (used and spare) bandwidth at the point of interest.

iv) *Time to profit* (Tp)—The initial time span during which the revenue earned accounts only for the infrastructure installation costs. The PIP decides how small the Tp should be (smaller Tp raises the rents for the NPs in the initial years).

Business Scenario: The business scenario is depicted in Table III and is discussed next. We assume that users are distributed across a Manhattan simplified street length (SSL) geometric model [25] with a span of 2×2 km^2 for calculating the fiber and trenching distances. In our business scenario, the infrastructure is designed to support a maximum of 16384 (2^{14}) subscribers. The business scenario has four NPs; $NP_u - NP_x$ (see Table III) with the characteristics mentioned in the market data of [20]. The smaller NPs in Table III can be SPs as well. The cost analysis is done over this assumed business scenario and is targeted for the European market. Below, we compare the CapEx and OpEx of GOAID-ODN with the two flavors of open access architectures as proposed in [2] (open access with point of unbundling (PoU) at the remote node and OLT). We also quantify the utilization ratios in GOAID-ODN.

TABLE III
BUSINESS SCENARIO [20], [21], [24]

NP	Subs. gain rate type	Growth	Initial users	type
NP_u	+0.25%	30%	20%	FTTP or WDM or TWDM over GOAID
NP_v	+1%	30%	5%	FTTP
NP_w	-0.25%	0%	5%	FTTP
NP_x	-1%	0%	20%	FTTP
Number of NPs : 4			Time to profit (Tp) : 5 years	
Subscribers supported : 16384				

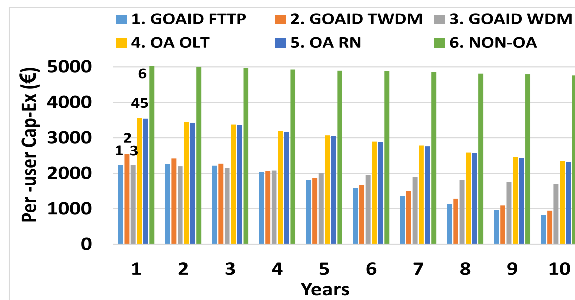


Fig. 8. Comparison of per user CapEx (OA—open access) 4–6 [3].

1) Comparison of CapEx: We compare the CapEx of the proposed schemes (in this paper) with those proposed in [2] and a vertically integrated infrastructure [11] in Fig. 8. The costs of the components (for CapEx calculation) have been taken from Table IV ([3], [19], [22–24]). To compare the CapEx and OpEx of the different schemes (listed below), we assume that the NPs are of type NP_u (see Table III) across the different schemes.

1) FTT over GOAID-ODN (GOAID FTT).
2) Typical TWDM over GOAID-ODN (GOAID TWDM).
3) WDM over GOAID-ODN (GOAID WDM).
4) Open access at OLT (OA OLT) with unbundling at manual wavelength router (MWR) using TWDM [3].
5) Open access at RN with unbundling at ODF (OA RN) [3].
6) Traditional vertically integrated scenario (non-OA) [11].

The annual Cap-Ex for a BP in GOAID-ODN is calculated by finding the required optimal resources from the expansion algorithm for a per-user bandwidth of 312 Mb/s (see Section III). This includes calculating the optimal number of access, feeder and distribution fibers, $RN_{2,z}$ and RN_1 ports, transceivers at the OLT and the required trenches ($d_{k,z}$, M_k and B_k). The CapEx for a BP in other schemes is calculated from their respective methodologies. This is divided by the number of users under that BP (see Table III) to derive the per-user CapEx. For

TABLE IV
COST AND POWER CONSUMPTION OF COMPONENTS [3], [19], [22]–[24]

Component		Cost (€)	Component		Cost (€)
Cost of trenching (in metro scenario)		35/m	Y branch		25
OLT shelf space (18 slots)		5000	Cost of distribution and feeder fiber		2.3/m
AWG (M:N)		30 × (M+N)	Cost of last mile fiber		1/m
PS (M:N)		10 × (M+N)	Cost of duct		2.8/m
Fast Switch		10000	Branching box		100
Patch Panel (home premises)		50	Street cabinet		200
Circulator		10	Patch Panel remote node)		200
Fixed Transceiver (OLT)		150	ONU (tunable transceiver)		100
Tunable Transceiver (OLT)		200	ONU (tunable transceiver)		75
Operational Expenditures		**Cost (€)**	**Operational Expenditures**		**Cost (€)**
Annual salary of technician for patching (1 every 50 users)		48000	Test equipment for monitoring		500
Cost of re-patching		40			
Component	**Power Budget**	**Power Cons.**	**Component**	**Power Budget**	**Power Cons.**
ONU line card	–	5 W	OLT rack		100 W
OLT line card	–	90 W	PIN photo-detector	−22 dB	1 W
SOA based fast switch	–	400 W	DFB laser (tunable)	9 dB	1.2 W
Slow switch (add-on dev.)	–	65 W	AWG (32×32)	−3 dB	–
Connector	−0.25 dB	–	Power splitter(1×32)	$3\log_2 N$ db	–

example if an NP has 96 subscribers from a region ($RN_{2,z}$) with a bandwidth demand of 312 Mb/s per user, then the expansion algorithm calculates the required resources as $d_{k,z} = 2$, $M_k = 2$ and $B_k = 2$ from (6) and (8). In addition, the NP needs to rent 96 last mile fibers, the associated trenches, ducts and branching boxes from the PIP. The PIP may require to install new AWGs at that $RN_{2,z}$ depending upon the value of n_z^{AWG} from (9). A similar approach is used to calculate the per-user OpEx.

It is observed from (see Fig. 8) that the per-user CapEx is the lowest for FTT over GOAID-ODN and highest for a vertically integrated infrastructure. Although, the Cap-Ex reduces for all the schemes with time, the reduction in the CapEx for FTT and typical TWDM over GOAID-ODN is significant. This is attributed to a better sharing, ID and a higher span (more users served by the same OLT) of GOAID-ODN. The higher scalability of GOAID-ODN (due to ID) allows more users to share the cost of the infrastructure (resources at the OLT, trenches, ducts, etc.), resulting in a rapidly decreasing per-user CapEx over the years. Thus, the benefits of ID support in GOAID-ODN is seen in the CapEx comparison and will also be highlighted in the comparison of power consumption. The per-user CapEx of WDM over GOAID-ODN is higher compared to the other open access schemes as a lesser number of users share the cost in WDM (shared ODN but dedicated transceivers).

2) Comparison of OpEx: We next show (see Table V) a comparison of the per-user OpEx in different open access architectures. It is observed that the per-user OpEx is much lower in GOAID-ODN (particularly FTT and typical TWDM over GOAID-ODN) compared to its counterparts as manual re-patching is not required when a user changes its NP. Re-patching is substituted by a change in the subscriber's wavelength in GOAID-ODN. The PIP only needs to patch the new users to the network in GOAID-ODN and hence, the OpEx is covered by the PIP. Thus if an NP desires to provide service to a user in a region

TABLE V
PER-USER OPEX [10]

Open Access Scheme	Per-user OpEx (€)	Open Access Scheme	Per-user OpEx (€)
GOAID FTTP	5	OA OLT	80
GOAID TWDM	5	OA RN	40
GOAID WDM	40	non-OA	5

to which it has no connection, it needs to rent the required fibers from the PIP. The PIP installs $RN_{2,z}$ and feeders according to the number of NPs (SPs) and users existing in that region. The typical WDM scheme over GOAID-ODN has higher per-user OpEx due to a lesser per-user sharing of the ODN. The open access schemes proposed by the authors of [3] have high OpEx, which include cost of human patching and patching equipment in addition to the essential requirements like monitoring equipment. The per-user OpEx of a vertically integrated BP [11] is small, for the obvious reasons that, re-patching is not required in the absence of subscriber gain rate. We observed that OpEx remains consistent with time.

3) Utilization Ratios of GOAID-ODN: Below we discuss the utilization ratios of different segments of fibers employed in GOAID-ODN. This helps us to reason the cost advantages obtained in GOAID-ODN. The open access architectures proposed in [3] are based on a single stage distribution network and hence cannot be compared with GOAID-ODN for utilization ratios. Assuming $N = 32$ (typically for dense-WDM) and $L = 10\,\text{Gb/s}$, each fiber can support a maximum of $32 * 10\,\text{Gb/s}$ in US and DS. In the last-mile fiber $10 * 32\,\text{Gb/s}$ is available for consumption (assuming connection to a maximum 32 NPs from the $RN_{2,z}$). This provides a utilization ratio of 1 ($utilized/available$). The distribution and feeder fibers connect to only one transceiver at a time for the FTT and typical

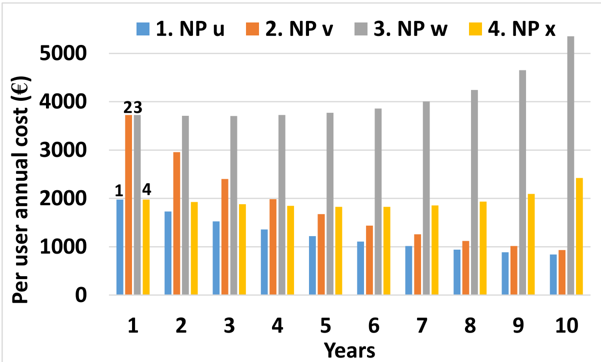


Fig. 9. Comparison of per-user expenditures (OpEx + CapEx).

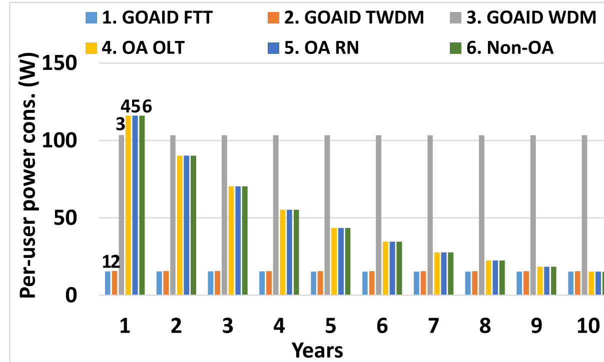


Fig. 10. Comparison of per-user power consumption of different schemes.

TWDM OLT schemes resulting in utilization ratio of $10/320$. For the typical WDM OLT scheme these fibers connect to all $N(= 32)$ transceivers at the OLT through the add-on distribution device resulting in utilization ratio of 1.

4) Analysis of Monopoly: With a large user base the CapEx is expected to be small. *A smaller per-user CapEx may provide the motive for monopoly to the big NPs (SPs).* However, we discuss in the following text with the help of Fig. 9 that monopolies are not established in the GOAID-ODN by assuming NPs of different sizes and behaviors (see Table III). An NP can be aggressive (better pricing as well as services) in its business policies to attract more customers. This is reflected in a positive subscriber gain rate as well as a higher growth rate of the NP (e.g., NP_u, NP_v in the discussed business scenario). From this knowledge we infer the behaviors of different NPs.

We observe that NP_u, and NP_x initially possess a big percentage of the user base, whereas NP_v and NP_w have small number of subscribers. Of the four NPs, it is evident that NP_u and NP_v perform aggressive business (provide better services at cheap rates) thereby achieving a high growth and subscriber gain rate. NP_w and NP_x are dormant NPs thereby having a small growth and negative subscriber gain rate (resulting in a depreciation in the number of subscribers). Due to a large user base initially, NP_u and NP_x have a cost advantage over NP_v and NP_w. However over time, NP_v achieves similar per-user costs as NP_u, due to an aggressive business strategy. This proves that monopoly (due to lower per-user CapEx) is not enjoyed by NPs with a large initial user base. Since NP_w and NP_x are dormant, their per-user costs increase with time. *Thus, GOAID-ODN ensures a competitive market as well as co-existence of different sizes of NPs with scope for expansion by ID.*

5) Comparison of Energy-Efficiency of GOAID-ODN: We make a comparison of the per-user power consumption of different schemes in Fig. 10 assuming the business scenario of Table III. With time, there is an increase in the number of users for the respective NPs (assumed of type NP_u in Table III). As such, more users share the power figures (listed in Table IV, [8]) of the active components at the OLT. Thus, a reduction in the per-user power consumption of all schemes is observed.

In initial years, the per-user power consumption figures for FTT and typical TWDM over GOAID-ODN are significantly less. This is attributed to a better flexibility of bandwidth sharing and superior scalability compared to the schemes proposed in [3]. In typical open access architectures [3], the bandwidth of a laser cannot be shared among multiple users without the loss of security. This requires more OLTs (active elements) in comparison to GOAID-ODN for a smaller user base. Eventually, when the network is completely populated, the per-user power consumption of all schemes are equivalent due to the complete utilization of all resources. The WDM scheme has the highest per-user power consumption as it requires user-dedicated resources (least sharing).

6) Reach of Different Schemes in GOAID-ODN: The FTT over GOAID-ODN (see Fig. 2) has an excellent power budget of 26.5 dB resulting in a reach of 78 km (calculated from the insertion losses of the different components given in Table IV), assuming a fiber loss of 0.34 dB/km [8]. The reach of typical TWDM and WDM over GOAID-ODN are 22 and 57 km respectively (power budgets of 7.5 and 19.5 dB). The lower reach of the TWDM/WDM over GOAID-ODN is due to the insertion loss of the add-on device. The difference in reach of these two schemes is due to dissimilar architectures of the add-on devices (see Section IV). Optical amplifiers can further extend the reach.

VII. Conclusion

The proposed GOAID-ODN is a completely passive open access ODN with minimal OpEx, high availability and low CapEx. ID support allows for low start-up costs, thus encouraging new players to start business with small investments. The cost benefits are attributed to bandwidth- flexibility, better utilization ratios and ID. ID also lowers the cost of expansion. The GOAID-ODN ensures co-existence by discouraging monopoly. Moreover, penetration in GOAID-ODN allows the users to choose their desired BP. Presence of physical-layer security, data security and privacy make the GOAID-ODN an attractive open access solution. The flexibility of bandwidth sharing and the support of ID make GOAID-ODN greener compared to the schemes proposed in the literature.

The FTT OLT employed over GOAID-ODN allows seamless expansion and bandwidth sharing. Moreover, backward compatibility of typical WDM and TWDM schemes with scope for ID and energy efficiency is also facilitated by GOAID-ODN. Unlike the present open access schemes, BPs with different granularities are supported at multiple entry points.

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