Load-Dependent Power-Efficient Passive Optical Network Architectures

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***Abstract*—Passive optical networks consume nearly 70% of peak power even when the network load is almost zero (i.e., off-peak). To reduce power consumption under low-load conditions, we propose the concept of a flexible network architecture. Each architecture is a unique combination of central office, subscriber, and end-user equipment variants. Three such architectures are proposed. The architecture that minimizes the overall power consumption of the network can be chosen provided its network performance is within an acceptable range. Using numerical evaluation, we observe that three of these architectures perform better than the others. We describe the network operation for these architectures and then evaluate their network performance using simulations. For two of the studied scenarios, it is shown that at least 35% power savings can be achieved by adopting a proposed architecture during off-peak network loads, without significant performance impact in terms of throughput and packet delay.**

***Index Terms*—Optical Access networks; Passive optical networks; Power efficient architectures.**

I. Introduction

Service providers typically design access networks so as to maximize revenues and minimize costs. Recently, operational expenses including power costs form a significant part of the overall costs. Thus, reducing power consumption is increasingly being considered when a technology choice decision is made by service providers.

Passive optical networks (PONs) offer a power-efficient solution to implement an access network. Time-division multiplexing PONs (TDM-PONs) standardized by the IEEE and ITU-T are being widely deployed [1]. A PON primarily consists of an optical-line terminal (OLT), remote node (RN), optical network units (ONUs), and end-user equipment (EN). The current PON standards define a specific role for an OLT and an ONU in the overall network operation. Using these standards, the equipment's hardware resources (transceivers, CPU, and memory resources) can be derived: (i) an OLT computes the upstream transmission schedule for all ONUs and informs the ONUs, and (ii) an ONU utilizes this transmission schedule to send packets to the OLT. Both the OLT and ONU must have a transceiver, CPU, and memory resources to support this control-message exchange. This approach facilitates mass manufacturing by defining a fixed role for network equipment, thereby reducing cost. The main idea of the paper is that introducing flexibility into each network equipment's role can help reduce operational costs.

For revenue maximization, network operators design and deploy PONs that can sustain high throughput even during peak-load conditions. However, the network is not designed to consume less power during low-load conditions. In this work, the concept of *flexible network architectures* that can consume reduced power during low-load conditions is presented.

To enable flexibility, different variants of network equipment, each with differing power requirements, are presented. Central office equipment (COE) can have variants that have different resource and power consumption profiles. Similarly, subscriber equipment (SE) and EN can also have variants. For a single user scenario, an architecture can use a combination of these variants that consumes the least amount of power. These equipment variants may not have sufficient hardware resources to support their role as specified by the standards. As the load increases, other combinations have to be used.

The contribution of this work is threefold: (i) proposing variants of COE, SE, and EN types, each with different resource and power consumption profiles; (ii) proposing several architectures based on combining these equipment variants subject to specified constraints; and (iii) evaluation of the power consumption and network performance of these architectures. Based on the evaluation, it is observed that a proposed architecture reduces power consumption by at least 35% during off-peak network loads without significant performance penalty in terms of reduction in throughput and packet delay.

The remainder of the paper is organized as follows: The background material is presented in Section II. The different equipment variants are presented in Section III. Next, the different architectures and their network operation are presented in Section IV. The performance evaluation architectures are presented in Section VI.

II. Background

This section presents the relevant background material.

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A. IEEE EPON Standard

The IEEE 802.3ah standard describes the details of a PON [2]. The main components of a PON are the OLT, RN, and ONU. A PON connects an OLT port in the provider side to multiple ONUs on the subscriber side. A PON uses one optical fiber from an OLT port to connect multiple ONUs. It uses a RN that splits and distributes signals received from the OLT port to multiple ONUs. These ONUs can be connected to desktops, laptops, or mobile equipment as needed at the subscriber side. This architecture forms the base architecture ($A0$) for the rest of this paper.

The network operation is as follows:

1) When the EN has a data packet to transmit, it adds a necessary header and trailer to create a valid stream of bits that is ready for transmission. The EN then sends this packet to the ONU connected to it.
2) The receiving ONU checks the data packet's integrity and stores it in its packet buffers.
3) The ONU waits for the next transmission opportunity message (*GRANT*) from the coordinating OLT. Upon receiving the *GRANT*, it transmits for the duration specified. At the end of transmission, the ONU transmits a *REPORT* message to inform its current buffer backlog status to the OLT.
4) Upon receiving an ONU's data packets and *REPORT* message, the OLT executes a *dynamic bandwidth allocation* algorithm to compute the next transmission time and duration for the ONU. This computation result is informed to the respective ONU using a *GRANT* message. This *REPORT-GRANT* message cycle gets repeated.

In this paper, a generalized terminology is used to refer to the components of a PON. The aim is to distinguish this equipment from the ones specified by the standards. The main components of a PON will henceforth be referred to as COE, FE, SE, and EN. COE, FE, and SE correspond to OLT, RN, and ONU, respectively. The legacy OLT, ONU, and EN used in architecture $A0$ are denoted by C_0, S_0, and E_0, respectively.

B. Related Work

This section presents significant related works that led to the current paper. To the best of our knowledge, defining different equipment variants and combining them to realize an architecture has not been attempted. So there are no prior works other than PON as specified by the standards described above. Most of the related works described here were used to derive equipment variants discussed in the next section.

In [3], a cloud remote-access network (CRAN) architecture has been proposed. This introduces an optoelectrical media converter (MC) to convert signals between the radio wireless domain and the optical domain. Here, all wireless signals are sent to a centralized server that processes and responds to these signals. In this work, the generalized MC concept has been adopted for use by PON EN that is assumed to utilize copper transceivers, unless mentioned otherwise.

A mechanism to reduce power consumption when operating at different network loads in a digital subscriber line (DSL) environment was presented in [4]. This is done using passive-line extenders (PEs) or active-line amplifiers (ALs) to concentrate DSL lines until it is worth deploying CPU and memory resources to process these lines. Since the PEs are passive, the power consumption is reduced significantly. This concept has been used in our work.

In the architecture proposed in this paper, it is assumed that COE will have optical interconnects between them so that network load can be aggregated in a similar manner. Commercially available OLT equipment such as [5] have multiple OLT ports on the same node. Hence, the interconnections and additional optical components can be added within the node. When there is scope for more power savings, interconnections across nodes can be introduced within a central office.

In previous work, an ONU architecture with reduced buffers was presented by our group [6] to reduce power consumption by about 34%. However, the ONU had to be modified to coordinate transmissions from different ENs, using a polling scheme. Likewise, the proposed architectures in this paper incorporate modifications to network operations.

In summary, different equipment variants are defined in this paper with different combinations of these variants used to define new power-efficient PON architectures.

C. Terminology

The basic terminology and definitions used in this paper are presented as follows:

- $\mathcal{T}(*)$ denotes the throughput of an architecture or a network equipment variant. It is the number of bits that can flow through the network or equipment in unit time. For instance, $\mathcal{T}(A0)$ stands for the throughput of architecture $A0$.
- N_* and n_*, respectively, indicate the total number of pieces of equipment (including the inactive ones) and the number of pieces of active equipment of a specific type $* \in \{c, s, e\}$. Here, c, s, and e stand for COE, SE, and EN, respectively. For instance, N_c denotes the number of COE ports and n_e the number of active ENs.
- $\mathcal{P}(*)$ denotes the power consumption of an architecture or a network equipment variant. For example, $\mathcal{P}(A0)$ and $\mathcal{P}(C_0)$, respectively, indicate the power consumed by PON architecture $A0$ and an OLT.

The power consumed by the architecture $A0$ [$\mathcal{P}(A0)$] is given by

$$\mathcal{P}(A0) = N_c(\mathcal{P}(C_0) + N_s(\mathcal{P}(S_0) + n_e\mathcal{P}(E_0))). \quad (1)$$

Here, N_c and N_s, are the number of OLT ports on the provider side and number of ONUs on the subscriber side, respectively, and n_e is the number of active end nodes. $\mathcal{P}(C_0)$, $\mathcal{P}(S_0)$, and $\mathcal{P}(E_0)$ are the power consumed by the OLT, ONU, and EN in architecture $A0$, respectively.

III. Equipment Variants

In this section, we present equipment variants for COE, SE, and EN. While field equipment (RN) variants are possible, this is not within the scope of the current paper.

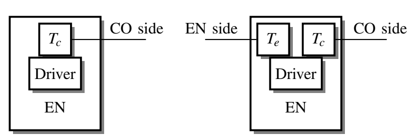
As mentioned earlier, types of equipment and their roles can be varied according to the current network requirements in a PON. In this work, three variants are considered for COE (C_0, C_1, C_2), two for SE (S_1, S_2), and two for EN (E_1, E_2).

A. End-Node Variants

The basic end node without any special transceivers, as described in [1], is referred to as E_0 for convenience. Figure 1 presents the two proposed EN variants.

The second EN variant, called E_1, is equipped with a special software device driver to directly interact with the COE. With EPON, the logical link identifier (LLID) is introduced and parts of the preamble are used for sending the transmission schedule. The device driver enables E_1 to understand the changes in preamble when frames are sent by an OLT. This EN variant can use auto-negotiation procedures to derive its data rate or can use a data rate of 1 Gbps or 10 Gbps where supported. The COE (C_0) must be capable of communicating with E_1 at any data rate chosen. Thus, the COE must support a wider range of data rates. PON also supports 1.25 and 2.5 Gbps speeds, but these are not widely supported by transceivers today. Thus, these data rates can be supported only when appropriate transceivers supporting these data rates are used in the EN.

The third variant, called E_2, is a specialized type of EN equipped with two transceivers. The first transceiver is used to communicate to the central office at 1.25, 2.5, or 10 Gbps. The second transceiver is used to communicate with other ENs sharing the SE. The data rate supported by this transceiver can be different from the first transceiver. This variant takes care of the packet processing and buffering that is normally carried out by a legacy ONU. In addition to the ONU functions, E_2 coordinates transmission between other ENs to itself. This is necessary because E_2 has only one EN-side transceiver, unlike a legacy ONU which can have multiple EN-side transceivers.



(a) E_1 having driver for COE communication (b) Special EN E_2

Fig. 1. EN variants: T_c transceiver facing CO side, T_e transceiver facing EN side.

B. Subscriber-Equipment Variants

Figure 2 presents the three subscriber-equipment variants. The fully functional legacy EPON ONU as described in [1] is referred to as S_0.

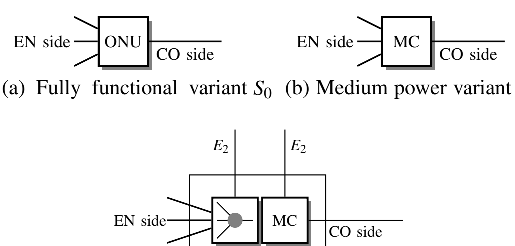
The first variant (S_1) is equipped with a MC to convert signals from ENs to the optical domain and back. This MC modulates the electronic signals (from a copper or wireless medium) from the ENs to the optical domain on a predesignated optical wavelength. These signals are propagated to the central office for further processing. In the return direction, it demodulates the signal and sends it over a copper or wireless medium.

The second variant (S_2) is equipped with a $1 \times N$ coupler and a MC. The $1 \times N$ coupler connects all ENs to the specialized EN (E_2). Using the star coupler, only one of these ENs can transmit to E_2 and only one EN can receive from E_2 at any given point in time. This restriction reduces the number of transceivers required at E_2. E_2 is equipped with two transceivers, one to communicate with other ENs (T_e) and another to communicate with the central office (T_c). In this variant, the MC also amplifies the signals between EN E_2 and the corresponding COE. This equipment does not contain any CPU or memory resources to process packets. It delegates all processing functions involving CPU and memory resources to the specialized EN, E_2.

Both S_1 and S_2 variants consume less power than S_0 by eliminating CPU and memory resources.

C. Central Office Equipment Variants

Figure 3 presents the three proposed COE variants. The first COE variant (C_0) is similar to a fully functional legacy OLT in terms of its CPU and memory resources. However, the proposed variant is also equipped with a $1 \times N$ coupler and amplifier in front of its transceiver. This enables C_0 to receive and process signals from other COEs that delegate their function to this COE. The coupler imposes



(a) Fully functional variant S_0 (b) Medium power variant S_1

(c) S_2 interoperable with special EN E_2

Fig. 2. Subscriber equipment variants: MC—media converter, CO—central office.

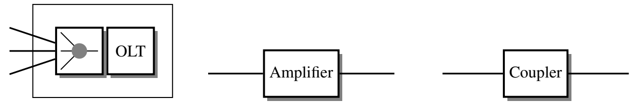
the restriction that only one packet can be received from across all active optical networks connected to a C_0. This can be relaxed by adding more transceivers to C_0 or by having optical switching elements for reconfigurability, but this is not considered in this paper. An amplifier can be placed in front of the transceiver to compensate for losses introduced by the coupler. In addition to these capabilities, the transceiver at C_0 must be able to communicate with ENs supporting data rates different from normal EPON data rates, such as 1 Gbps.

The second variant, called C_1, is similar to C_2 in terms of function delegation to another COE. However, it is also equipped with a line amplifier to amplify the signals from (and to) the ONUs. The C_1 variant can be used to boost the signal power so that after amplification, the receiver at C_0 can decode the signal at an acceptable bit-error rate. C_1 amplifies signals from the C_0 to the ONU to compensate for losses if any are introduced by the additional optical circuitry introduced in the C_0 variant. The line amplifier consumed more power when compared to C_2.

The third variant, called C_2, has a passive coupler that propagates the signals received from the subscriber side to another COE connected to it. This results in a simple delegation of functions to another COE until a predefined level of load aggregation is achieved. With this capability, only a small number of C_0s have to be active at a time, while supporting the current network load.

As we discussed earlier, the new variants C_1 and C_2 require C_0 to have interconnections within the node or between nodes.

This section has presented the different equipment variants in a PON. In the next section, architectures by combining these equipment variants are described.



(a) Fully functional variant C_0 (b) Medium power variant C_1 (c) Passive variant C_2

Fig. 3. COE variants.

IV. Architectures

This section describes the proposed architecture variants $A1$, $A2$, and $A3$. These variants were generated using a formal language notation with constraints presented in Appendix A. Architectures $A1$, $A2$, and $A3$ are represented, respectively, by DAPD, DAPPD, and DADAPD in formal language notation. Figure 4 presents the details of the proposed architectures. Architecture $A0$ refers to the existing legacy PON architecture, as described in Section II.

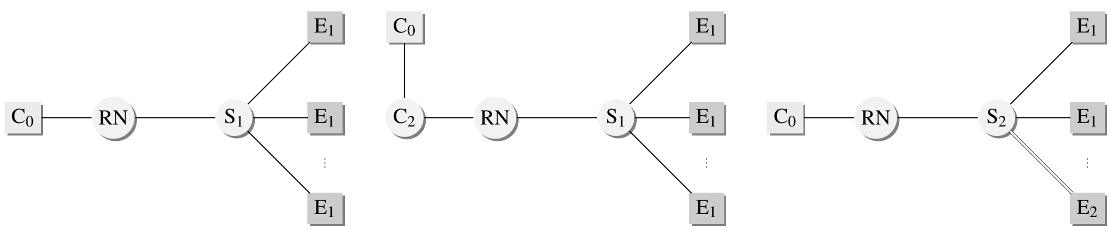
A. Architecture A1

The $A1$ architecture is designed to deal with scenarios when a small number of end nodes are active. In this architecture, the SE, the equivalent of the ONU, provides the minimum function of converting signals between optical and electrical domains. The architecture differs from $A0$ as follows. As seen in the block diagram [Fig. 4(a)], S_0 is replaced by S_1 and the plain EN variant E_0 is replaced by E_1. This change means adding a driver to directly interact with fully functional COE variant C_0. Since the EN (E_1) is directly interacting with the COE (C_0), the transceivers on both sides must support the line-data rate to be used. With this, power savings will result but with a decrease in throughput when 1 Gbps is the line-data rate. This architecture is not suitable when a large number of ENs are active ($n_e > N_s$), since it increases the scheduling load on the COE.

The timing diagram for network operation of $A1$ is presented in Fig. 5(a). The steps are (a) when the EN E_1 has a packet to be sent, it stores the packet in its packet buffer and waits for the GRANT from C_0; (b) after receiving the GRANT from C_0, it transmits as many buffered packets that fit the allotted duration; (c) the E_1 then sends a REPORT message indicating the current buffer backlog to the C_0 requesting a subsequent transmission opportunity; and (d) the C_0 receives this REPORT message from all E_1 nodes and computes the transmission schedule and informs the ENs.

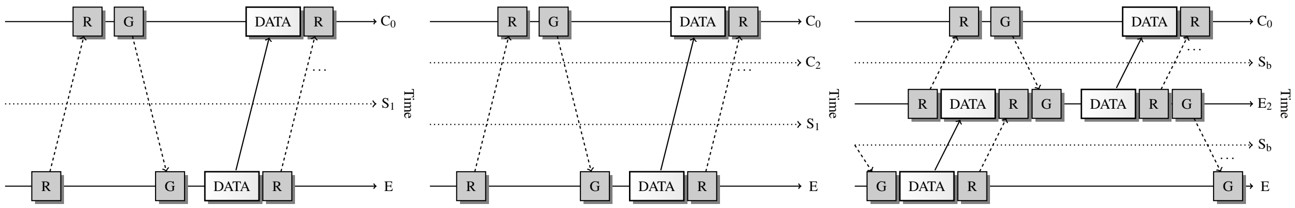
In the downstream direction, every COE sends packets destined to ENs, using broadcast. Every EN filters packets not destined to it. In the worst case, an EN must filter packets at the COE-EN line-data rate of 1 Gbps. The packet format used for 1 Gbps Ethernet and IEEE EPON are more or less similar. The LLID is specific to the EPON standard. Thus, existing network interface cards and device drivers can be adapted to work with EPON.

The main advantage of this architecture is that it can provide significant power savings, as computed below:



(a) A1 (b) A2 (c) A3

Fig. 4. Proposed PON architectures.



(a) A1 (b) A2 (c) A3

Fig. 5. Timing diagram for different PON architectures: G = GRANT, R = REPORT.

$$\mathcal{P}(A1) = \mathcal{P}(A0) - N_c N_s(\mathcal{P}(S_0) - \mathcal{P}(S_1)). \quad (2)$$

Here, N_c and N_s are the number of provider ports and subscribers in a network. $\mathcal{P}(A0)$ and $\mathcal{P}(S_0)$ denote the power consumed by architecture $A0$ and the S_0 SE variant, respectively. $\mathcal{P}(S_1)$ is the power consumed by the S_1 SE variant. Since the difference $\mathcal{P}(S_0) - \mathcal{P}(S_1)$ is around 3 W, this architecture can save a considerable amount of power in the network.

B. Architecture A2

The architecture $A2$ is designed to mainly reduce the number of C_0 instances when a fewer number of schedulable nodes (E_1 or E_2 or S_0) are active. This architecture has COE variant C_1 or C_2 on the provider side in front of the C_0 variant. This facilitates COE nodes to delegate their processing to C_0 instances. Thus, traffic incident on C_1 and C_2 variants is aggregated on a small number of C_0 instances so that other C_0 instances can be put to sleep to save power. The details and the timing diagram for architecture $A2$ are presented in Figs. 4(b) and 5(b), respectively. The network operation is very similar to the $A1$ architecture on the subscriber side.

Similar to the work in [4], this architecture varies the number of active C_0 instances according to the network load. Thus, the maximum throughput of the network is limited by the combined line rate that can be handled by the number of active C_0 instances. In the extreme case, when there are only a small number of active subscribers, their traffic can be aggregated on a single C_0 instance. This instance can compute the schedule for all the subscribers as if they were connected to the same OLT port in the legacy environment. The number of active subscribers that can be handled by a C_0 instance is referred to as η.

The power consumed by the network is given by

$$\mathcal{P}(A2) = \mathcal{P}(A1) - \left(N_c - \left\lceil \frac{n_c N_s}{\eta} \right\rceil\right)\mathcal{P}(C_0). \quad (3)$$

Here, $\mathcal{P}(A1)$ is the power consumed by architecture $A1$; N_c and N_s are the number of COE ports (both C_1 and C_0 put together) and number of S_1 nodes, respectively; n_c is the number of active COE ports and η is the maximum number of nodes that can be scheduled by an OLT instance; and $\mathcal{P}(C_0)$ is the power consumed by one C_0 instance.

C. Architecture A3

Architecture $A3$ is designed to reduce the number of active EN-side transceivers on the SE. By using a coupler at S_2, the channel between E_1 and E_2 becomes multipoint to point. In this architecture, SE variant S_2 delegates all legacy ONU functions to the specialized EN (E_2), with two links connecting to S_2. Of these two links, one is used for communicating with other ENs (E_1 or plain E_0). The provider side remains unchanged. The details of the proposed $A3$ architecture are presented in Fig. 4(c).

It is assumed that the CO-side transceiver (i.e., T_c) of E_2 can be operated at higher rates supported by the COE (either 10 Gbps or 2.5 Gbps) and the other transceiver (i.e., T_e) at the rate supported by other ENs. Thus, the maximum throughput is limited by the maximum data rate supported by the E_2 CO-side transceiver.

In terms of network operation, EN E_2 coordinates packet transmissions to and from other ENs. For this, the existing one-level polling scheme used in $A0$ is extended to two levels. In the first level, COE and E_2 will participate in the scheduling process. In the second level, E_2 will schedule the rest of the ENs using GRANT-REPORT message exchanges. This can be useful in networks where E_2 is already a special node performing additional functions (e.g., caching function) for the local network or when many ENs (say five or more) generating less traffic are connected to a SE. Instead of keeping all transceivers in the ON state, the SE uses the PE function to pass the signals between E_2 and other ENs. In Fig. 5(c), the conversations between E_2 and E_0 at the second level and between E_2 and C_0 at the first level are presented.

In the downstream direction, the COE uses the LLID of the special EN E_2 when sending packets for ENs connected through an E_2. Based on its LLID, E_2 filters out packets received from the COE. E_2 forwards packets destined to other ENs on the EN side transceiver (T_e).

The power consumed by this architecture is given by

$$\mathcal{P}(A3) = \mathcal{P}(A1) + N_c N_s n_e \mathcal{P}(E_2). \quad (4)$$

Here, $\mathcal{P}(E_2)$ is the additional power consumed by the E_2 CO-side transceiver T_c. This architecture offers better power savings when the power consumed by transceivers on a legacy ONU is more than the power consumed by the additional transceiver at E_2 ($n_e \mathcal{P}(S_0) > \mathcal{P}(E_2)$).

This section presented the network operation of $A1$, $A2$, and $A3$. In Appendix A, six valid architectures have been derived. However, the network operation for the remaining three architectures derived is not presented here. As mentioned in Appendix A, they are similar to the architectures described in this section.

The next section presents the evaluation of the architectures at different network loads.

V. Numerical Evaluation

This section presents the numerical evaluation of the architectures, based on the equations presented in Section IV. Power is computed for different architectures under varying load conditions using Eqs. (2)–(4). For the digital electronic components, 33% of the peak-power consumption is considered as the dynamic range of power; the remaining 67% of the power is considered as the static power consumed [7]. Using this, the power-to-throughput ratio ($[\nu = \mathcal{P}/\mathcal{T}]_*$, where $* \in \{A0, A1, \ldots\}$), is computed for all six architectures. Here, $\mathcal{P}$ and $\mathcal{T}$ indicate power consumption and throughput for an architecture. The objective is to identify the architecture that has the smallest power-to-throughput ratio. The input parameters, namely the number of active EN(n_e), number of active COE ports (n_c), number of active SE nodes (n_s), number of nodes scheduled by one C_0 instance (η), and input load factor on the network, are varied. The load factor ρ is the ratio of input load to the maximum load that can be applied to the network.

The power-consumption values used for evaluation are shown in Table I. Here, $\mathcal{P}$(Eqpt) and $\mathcal{P}$(Trx) indicate the power consumed by network equipment and transceivers, respectively. As a conservative estimate, the power consumed by an OLT port (C_0) is taken to be 30 W. This is derived from the value of 1.5 kW consumed by a Motorola AXS1800 OLT [5] supporting 1500 users (48 OLT ports and 32 ONUs per OLT port). In reality, the power consumption of an OLT port cannot be equally distributed across all ports, and more than 66% of power (1 kW) is consumed when OLT is idle [7]. So this is a conservative estimate of the power consumption of an OLT port. The S_0 power consumption of 4 W is derived from the 6 W power consumption reported by Sumitomo's FTE6183 [8] and by appropriately reducing the power consumed by its transceivers.

Figure 6 presents the architecture that has the minimum power-to-throughput ratio for different values of n_e, n_c, n_p, and ρ. In the graph, architecture $A0$ is denoted by ("+"), $A2$ by ("×"), $A1$ by ("Δ"), and $A3$ by ("○"). The outer x axis indicates the number of ENs, the outer y axis indicates the number of ONU nodes, the inner x axis indicates the input load factor, and the inner y axis denotes the number of active OLT ports, respectively. The value of η is assumed to be 64. For instance, the architecture that has a minimum power-to-throughput ratio for $n_e = 1$, $n_s = 64$, $n_c = 64$, $\rho = 0.4$ is $A2$ as seen from the 4th point in the top row of the top-left plot.

TABLE I
Power-Consumption Values Used for Numerical Analysis

Equipment	C_1	C_0	S_1	S_2	S_0	E_2	E_1
$\mathcal{P}$(Eqpt)	1.05	30.0	1	2	4	—	0
$\mathcal{P}$(Trx)	—	1.25	—	—	1	1.5	—

From Fig. 6, it can be observed that $A0$ does not offer the minimum power-to-throughput ratio for low load conditions across all scenarios. When 64 C_0 instances are active, $A0$ is suitable only when the load factor is 0.5 or higher. This reinforces our hypothesis that the existing PON architecture is not suitable for low- and medium-load conditions. Of the scenarios studied, 35% (63 out of 180) can be handled better by adopting the architectures proposed in this paper. The estimated network-wide power consumptions for $n_e = 1$, $n_s = 1$, $N_c = 64$, and $\rho = 0.1$ are 5.15, 3.21, 2.21, and 3.31 kW for $A0, A1, A2$, and $A3$, respectively. The maximum expected throughput with upstream and downstream put together for $A2$ is 4 Gbps with $\eta = 32$, and other architectures support a one-tenth network load of 32 Gbps. When operating at low loads, a power savings of 2 kW can be saved without loss in throughput. With $A2$ in an extreme case, 3 kW of power can be saved at full load by losing 75% of throughput.

Since not all ONUs are expected to be active at all times in architecture $A0$, it is beneficial to use $A1$, $A2$, and $A3$ architectures where suitable. For instance, every ONU can be built with an option to switch between S_0 and S_1 or S_2 depending on the network load. With this approach, a significant amount of power can be saved in a given day. In the next section, the network performance of these three architectures using simulations is presented.

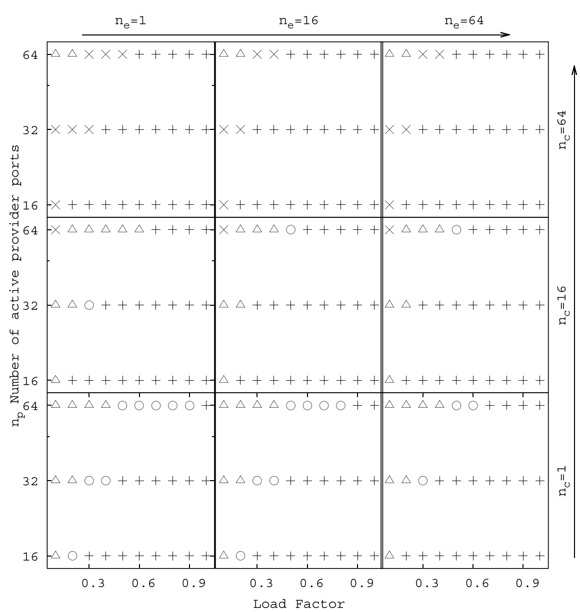


Fig. 6. Numerical result of minimum power-to-throughput ratio for all architectures under varying load: $\eta = 64$, $n_e \in \{1, 16, 64\}$, $n_c \in \{16, 32, 64\}$, $n_s \in \{1, 16, 64\}$, $\rho \in \{0.1, \ldots, 1.0\}$ in steps of 0.1. Legends: $A0$ ("+"), $A1$ ("Δ"), $A2$ ("×"), and $A3$ ("○").

VI. Simulation Results

This section presents simulation-based performance results. The simulation model was developed using SimJava [9] (a Java-based simulation package) to evaluate the network performance of packets flowing from the ENs to the COE. A Poisson traffic source at every EN and a sink at the COE are assumed. The gated dynamic bandwidth-allocation algorithm described in [10] that grants the quantum demanded by the SE was used in the COE. Packet delay and throughput were used as metrics. Packet delay is taken as the time between generation of a packet at an EN and the time it is received by a C_0. Throughput measured at the C_0 is based on the number of bytes of data packets received in unit time. Each simulation experiment was repeated ten times to estimate packet delay with 95% confidence. The simulation parameters are summarized in Table II. For $A1$ and $A2$, the transceivers at the central office were operated at a 1 Gbps data rate. The same data rate was used for all EN transceivers.

TABLE II
Simulation Parameters

Parameter	Value
ONU-OLT distance	Uniform distribution (15, 20) km
EN-ONU distance	Uniform distribution (100, 150) m
Message processing time	1 μs
Packet length	Uniform distribution (64, 1500) bytes
Network load	From 250 Mbps to 2.5 Gbps per OLT port
Report message size	64 bytes
Grant message size	64 bytes
EN-ONU line rate	1 Gbps
ONU-OLT line rate	2.5 Gbps
ONU packet buffer size	2 MB
EN packet buffer size	256 kB

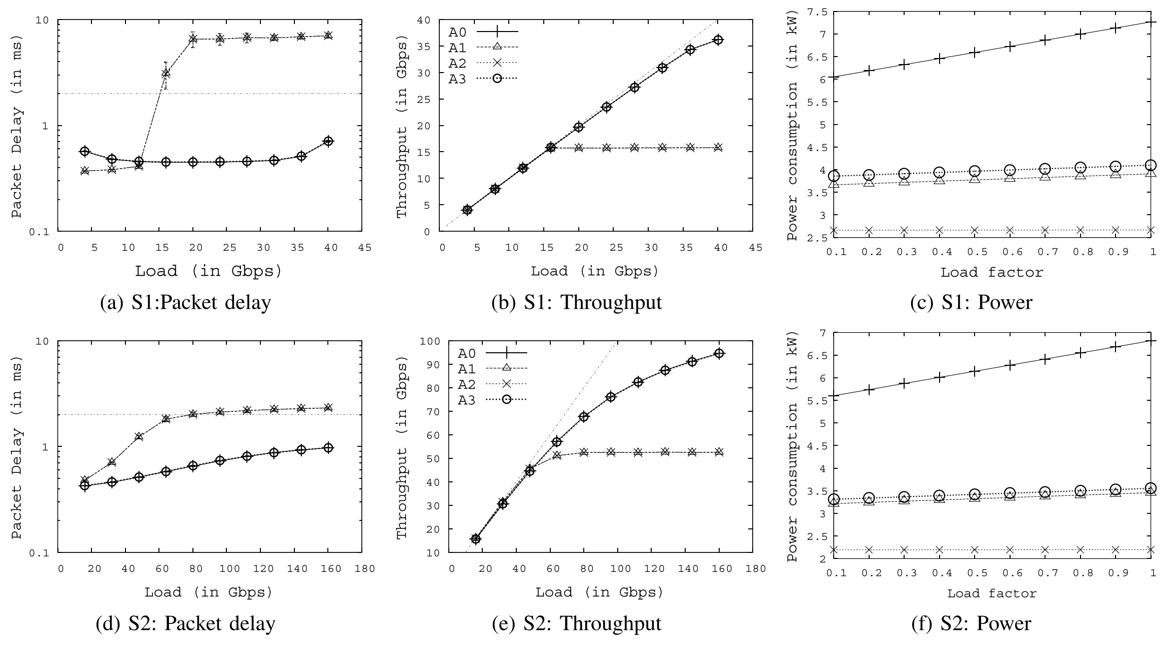
A. Network Performance of Different Architectures

In the operational range, network performance expectations are as follows: Throughput is expected to be responsive and linear with respect to the load applied to the network and packet delay is expected to be within 2 ms as specified in [11]. To evaluate the network performance two scenarios were considered. For the first scenario ($S1$), the parameter values $n_e = 4$, $n_s = 8$, and $n_c = 16$ were used. For the second scenario ($S2$), the parameter values $n_e = 1$, $n_s = 1$, and $n_c = 64$ were used.

The performance results with varying load are presented in Fig. 7. Under low loads, architectures $A0$ and $A3$ follow a similar trend in terms of throughput and packet delay. The packet delay and throughput trends of architectures $A1$ and $A2$ are similar. The number of active ENs n_e is small to observe any significant difference between $A1$ and $A2$. In terms of power consumption, $A2$ consumes the least amount of power. Architectures $A1$, $A3$, and $A0$ consume more power in an increasing order compared to $A2$.

In scenario $S1$, $A1$ and $A2$ experience acceptable packet delays for up to a load of 12 Gbps, beyond which throughput saturation and abrupt increase in packet delay are observed. At least 35% and 52% power can be saved by adopting $A1$ and $A2$, respectively, compared to $A0$.

In scenario $S2$, the power consumption difference between $A3$ and $A1$ architectures is narrower than with scenario $S1$. This can be attributed to the lower number of active ENs (n_e) in $S2$. At least 57% and 38% power can be saved when using $A2$ and $A1$, respectively. Throughput saturates at 48 Gbps network load for these



(a) S1:Packet delay (b) S1: Throughput (c) S1: Power

(d) S2: Packet delay (e) S2: Throughput (f) S2: Power

Fig. 7. Packet delay, throughput, and power for selected scenarios. $S1$: $n_e = 4$, $n_s = 8$, $n_c = 16$, and $S2$: $n_e = 1$, $n_s = 1$, $n_c = 64$.

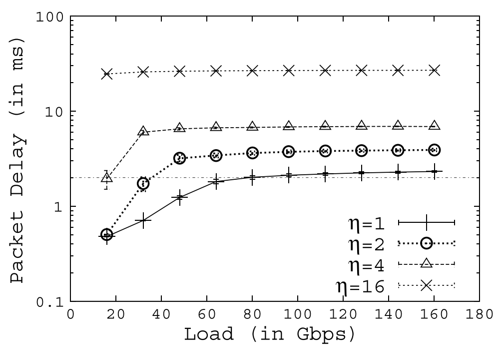
architectures; beyond this load, packet delay is well above 2 ms.

So far, we observed that architectures $A1$ and $A2$ are suitable for low-load conditions. Within the operational range, a significant amount of power can be saved in both scenarios. Architecture $A3$ is suitable even at high network loads.

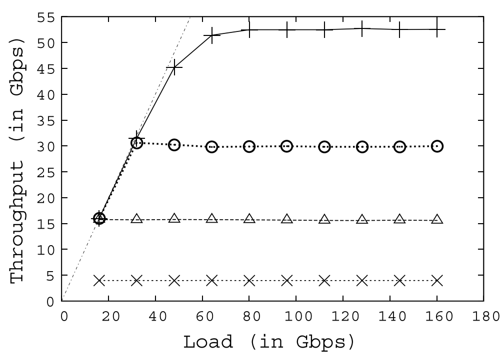
B. Effect of η on $A2$

Earlier the relationship between η and power consumption was presented using Eq. (3). However, the relationship between η and network performance needs to be studied. Four scenarios where η takes values from the set {1, 2, 4, 16} are considered. The scenarios are $(n_e = 1, n_s = 1, n_c = 64)$, $(n_e = 1, n_s = 2, n_c = 32)$, $(n_e = 1, n_s = 4, n_c = 16)$, and $(n_e = 4, n_s = 4, n_c = 4)$ in terms of the number of nodes. These networks are subjected to the same input load. Packet delay and throughput are measured.

The performance results for $A2$ with varying η are presented in Fig. 8. It can be seen that with an increase in η, the saturation throughput reduces from 52.5 Gbps for $\eta = 1$ to 3.98 Gbps for $\eta = 16$. This is expected with an increase in η. With higher η, the number of C_0 instances required is reduced. At 250 Mbps network load per C_0 instance, the packet delay increases from 479 µs when $\eta = 1$ to 2.46 ms when $\eta = 16$. At $\eta = 16$, the packet delay is more than 2 ms. Thus, the applied network load must be less



(a) Packet delay



(b) Throughput

Fig. 8. Packet delay and throughput for $A2$ architecture, with different values of η.

than 4 Gbps when $\eta = 16$. The corresponding power saved is conservatively around 450 W (15×30). This confirms that by choosing the right value of η for the given network load, power consumption of the network can be minimized and at the same time packet delay and throughput can be maintained within the operational range.

VII. Conclusions

This paper proposed flexible network architectures to relax the fixed mapping of role to network equipment. Several equipment variants were presented, based on which six network architectures were derived, of which three were studied in detail. On evaluation, it was found that three architectures with COE having a passive coupler and SE having an optoelectrical MC converter ($A2$), SE having an optoelectrical MC ($A1$), delegating ONU's functions to a special EN ($A3$), and the legacy PON architecture $A0$ in that order are suitable when network load is increased. The simulation results show that architectures $A1$ and $A2$ have limited operational range in terms of the network load they can handle. For the studied scenarios, by adopting a proposed architecture at least 35% less power can be saved than $A0$.

Appendix A: Formal-Language-Based Architectures

A *formal-language* notation with constraints is used to derive all architectures that are valid and satisfy the constraints for a sample deployment. The different equipment variants are categorized into three broad groups $\{P, A, D\}$. Group P refers to equipment variants that do not consume any electrical power, group A refers to equipment variants that do not contain digital components such as CPU or memory (they consume a moderate amount of power), and group D refers to all other equipment variants (and consume high levels of power). Thus, $P = \{C_2, RN\}$, $A = \{C_1, S_1, S_2\}$, and $D = \{C_0, S_0, E_1, E_2, E_0\}$.

A. Formal-Language Notation

In this paper, a Mealy's machine [12] from Finite Automata theory has been used to derive architectures for given deployment parameters. This machine consists of states, transition input and output, and transition logic to move across states. There is one initial state and there can be multiple terminal states. Considering one state transition at a time, when an input I is given to the machine currently at state S, it evaluates an output O. Based on the output O, it moves to the next state S'. The transition logic takes I and S as inputs to produce the output O. With this brief background, the problem formulation is presented further. Refer to [12] for further reading on Mealy's machine.

The network path between an EN and the COE is loosely mapped to its equivalent architecture. This path is made up of equipment encountered in a sequence starting from an EN to the COE. This network path is represented by a word from a formal language ($\mathcal{L}$) using regular grammar. Here, we present the regular grammar and briefly introduce the terminology required to understand the rest of the paper.

Regular grammar consists of a set of symbols and their production rules. Terminal and nonterminal symbols constitute the alphabet of the language. A terminal symbol does not have a production rule that takes it as an input to create a new word, whereas a nonterminal symbol has one or more production rules associated with it. Nonterminal symbols contain one special symbol called the starting symbol from where the derivation process starts.

Any production rule associated with a nonterminal symbol that is part of the current language can be used to extend the language by replacing the nonterminal symbol with the output of the production rule. The output of a production rule can also contain nonterminal symbols thus continuing the language-derivation process. The process of derivation using regular grammar results in a derivation tree. This derivation process continues until all production rules are exhausted across all branches of this tree. At the end of the derivation process, every valid *word* in the language contains only terminal alphabets. For a complete description of regular grammar and derivation processes one can refer to [12].

For the current problem, the grammar for the language $\mathcal{L}$ has three terminal symbols $\{\mathrm{P}, \mathrm{A}, \mathrm{D}\}$ representing equipment groups and nonterminal symbols $\{\boldsymbol{S}, \boldsymbol{X}, \boldsymbol{Y}\}$, where $\boldsymbol{S}$ is the starting symbol and λ is an empty string. The set of production rules is $\{\boldsymbol{R}_1\!:\!\boldsymbol{S} \to \mathrm{D}\boldsymbol{S}\mathrm{D}$, $\boldsymbol{R}_2\!:\!\boldsymbol{S} \to \boldsymbol{X}\mathrm{P}\boldsymbol{Y}$, $\boldsymbol{R}_3\!:\!\boldsymbol{X} \to \mathrm{AD}\boldsymbol{X}$, $\boldsymbol{R}_4\!:\!\boldsymbol{X} \to \mathrm{DD}\boldsymbol{X}$, $\boldsymbol{R}_5\!:\!\boldsymbol{X} \to A$, $\boldsymbol{R}_6\!:\!\boldsymbol{X} \to \mathrm{D}$, $\boldsymbol{R}_7\!:\!\boldsymbol{Y} \to \mathrm{P}\boldsymbol{Y}$, $\boldsymbol{R}_8\!:\!\boldsymbol{Y} \to \mathrm{A}\boldsymbol{Y}$, and $\boldsymbol{R}_9\!:\!\boldsymbol{Y} \to \lambda\}$. The transition logic output is a three-tuple vector made up of $\langle \gamma, \mathcal{P}, \boldsymbol{B} \rangle$. Here, γ can take a value from the set $\{V, I, C\}$. They denote valid, invalid, and continue, respectively. When invalid output is detected, the derivation process on that branch stops. When continue is detected, the derivation process can continue along the branch. When valid is detected, a valid architecture is found. $\mathcal{P}$ and $\boldsymbol{B}$ keep track of the current power consumption and power-budget values. The transition constraints consider these values to compute γ for the state.

Transition constraints: The power-consumption constraint is represented by $\ell_1\!:\!\mathcal{P} > \mathcal{P}(A_0)?\boldsymbol{I}\!:\!\boldsymbol{C}$ and the power-budget constraint is represented by $\ell_2\!:\!\boldsymbol{B} < \boldsymbol{B}'?\boldsymbol{I}\!:\!\boldsymbol{C}$. Here, $\boldsymbol{B}$ denotes the power-budget state variable and $\boldsymbol{B}'$ is the minimum power budget to operate the network. Similarly, $\boldsymbol{O}'$; indicates the SNR margin required to accommodate a line amplifier at the central office. Typically, this considers the noise figure of the amplifier in addition to losses due to fiber length and the splitter/combiner. $\boldsymbol{B}(*)$ denotes the insertion loss of specific equipment. For instance, $\boldsymbol{B}(RN)$ denotes the insertion loss of a RN. These constraints are applied whenever the corresponding value ($\mathcal{P}$ or $\boldsymbol{B}$) change happens according to the transition table (Table III). Initially, the state vector is initialized with $\mathcal{P} = 0$ and $\boldsymbol{B} = 0$. Operators $\underset{=}{+}$ and $\underset{=}{-}$, respectively, denote addition and subtraction to the current value of the state variable on the left-hand side.

TABLE III
TRANSITION TABLE FOR MEALY'S MACHINE

Rule	Expansion	Changes to $\mathcal{P}$ and $\boldsymbol{B}$	Values for γ
$\boldsymbol{R}_1$	$\boldsymbol{S} \to D\boldsymbol{S}D$	$\mathcal{P} \underset{=}{+} \mathcal{P}(E_0) + \mathcal{P}(C_0)$	I, C
$\boldsymbol{R}_2$	$\boldsymbol{S} \to \boldsymbol{X}P\boldsymbol{Y}$	$\boldsymbol{B} \underset{=}{-} \boldsymbol{B}(RN) + \boldsymbol{B}(OF)$	I, C
$\boldsymbol{R}_3$	$\boldsymbol{X} \to \mathrm{AD}\boldsymbol{X}$	$\mathcal{P} \underset{=}{+} \mathcal{P}(E_2) + \mathcal{P}(C_2)$	I, C
$\boldsymbol{R}_4$	$\boldsymbol{X} \to \mathrm{DD}\boldsymbol{X}$	$\mathcal{P} \underset{=}{+} \mathcal{P}(E_0) + \mathcal{P}(S_0)$	I, C
$\boldsymbol{R}_5$	$\boldsymbol{X} \to A$	$\mathcal{P} \underset{=}{+} \mathcal{P}(S_1)$	V, I, C
$\boldsymbol{R}_6$	$\boldsymbol{X} \to D$	$\mathcal{P} \underset{=}{+} \mathcal{P}(S_0)$	V, I, C
$\boldsymbol{R}_7$	$\boldsymbol{Y} \to P\boldsymbol{Y}$	$\boldsymbol{B} \underset{=}{-} \boldsymbol{B}(C_2)$	V, I, C
$\boldsymbol{R}_8$	$\boldsymbol{Y} \to A\boldsymbol{Y}$	$\boldsymbol{B} > \boldsymbol{O}'?\boldsymbol{I}\!:\!\boldsymbol{C}$	V, I, C
$\boldsymbol{R}_9$	$\boldsymbol{Y} \to \lambda$	—	—

From the table, whenever rule $\boldsymbol{R}_2$ is applied, the power budget is reduced by the insertion loss of RN (denoted by $\boldsymbol{B}(RN)$) and the loss due to the optical fiber (denoted by $\boldsymbol{B}(OF)$) to be deployed. Power consumption is increased when rule $\boldsymbol{R}_1$ is applied. Every time the $\boldsymbol{R}_7$ production rule is applied, the power budget is reduced by the corresponding equipment's insertion loss and the power budget constraint is applied. When the power budget goes below acceptable levels (–20 dB for IEEE EPON), it is treated as invalid. For production rules except $\{\boldsymbol{R}_2\!:\!\boldsymbol{S} \to \boldsymbol{X}P\boldsymbol{Y}$, $\boldsymbol{R}_7\!:\!\boldsymbol{Y} \to \mathrm{P}\boldsymbol{Y}\}$, power consumption transition constraint ℓ_1 is applied. When rule $\boldsymbol{R}_8$ is considered, C_1 amplifies noise along with the signal. When the input OSNR of the amplifier is lower than threshold $\boldsymbol{O}'$, the output OSNR will be insufficient for the receiver to detect signals at the same bit-error rate. Alternately, the $\boldsymbol{Q}$-factor of the signal can be computed and tracked as a new state variable when more than one amplifier can be deployed. This scenario is not considered as more than one amplifier is unlikely to be deployed at the central office for a 20 km PON.

Observations:

1) *When the minimum power budget is not met, the derivation process must be stopped on this branch.*

   When the minimum power budget is not met at the current state, it means that by having a receiver at this state of the derivation process, optical signals cannot be recovered with the same bit-error rate. Thus, any other equipment added to the branch cannot recover the signals at the same bit-error rate that is already below the receiver sensitivity level. Thus, derivation along this branch must be stopped.

2) *When the current power consumption exceeds the maximum power consumption, the derivation process must be stopped on this branch.*

   Equipment power-consumption values (considered in this paper) are either greater than or equal to zero watts. For instance, the C_2 passive equipment variant consumes zero watts. Thus, when the current power consumption exceeds the maximum power consumption, any additional equipment will not be able to bring down the power consumption. Thus, derivation along this branch must be stopped.

Advantages: The formal-language approach used in this paper is simple and has the following advantages over the equivalent ILP formulation:

1) **Enumeration**: Enumeration of all feasible solutions is possible. As shown later in this section, all feasible solutions for a sample deployment are enumerated.
2) **Tradeoff relationships**: The tradeoff with respect to power and cost can be interpreted from the formal language. When a network operator is ready to change the network power consumption or cost by a percentage (say x) and is interested to know the new architectures that are feasible under this deployment scenario, the formal-language representation will be able to answer this question.
3) **Equivalence classes**: Two architectures and their equivalence can be established with the formal-language approach. With this approach, the network performance of equivalent architectures can be derived once network performance for one of these architectures is known.
4) **Avoiding infeasible solutions**: The formal representation intuitively avoids exploring solutions in the infeasible range, whereas modeling infeasible regions to stop ILP from exploring infeasible regions is comparatively complex.

B. Proposed Architectures

A network-deployment example is considered here. The maximum power budget utilized across all optical distribution networks connected to a central office is 18 dB. Thus, 2 dB headroom is available out of the total 20 dB power budget for a class B fiber-based EPON deployment. Assume that the COE interconnection using optical fiber requires less than a 1 dB power budget and a C_2 (a passive coupler) has an insertion loss of about 1 dB. At the subscriber end, just 10 ONUs are active across 16 central office ports supported by a central office. Every ONU has at most two ENs connected to them. Each C_0 has sufficient CPU and memory resources to compute the schedule for at most 32 nodes. These nodes can either be ONUs or ENs. The amplifier variant (C_1) at the central office is not considered. One C_0 instance consumes around 30 W of power and the C_2 instance does not consume any power (0 W). The power consumed by S_1, S_2, and S_0 is taken to be 1, 2, and 4 W, respectively. The incremental power consumed by E_2 is taken to be 1.5 W for the additional transceiver T_c. Taking the power of E_0 to be 50 W (the power consumed by a laptop), $\mathcal{P}(A0)$ (base architecture power) is 84 W.

The word tree is presented in Fig. 9. This tree presents a limited snapshot of all possible combinations of alphabets $\{D, A, P\}$. It starts at an empty root node on the left-hand side. Every path from the root to a valid node (in green) is a valid architecture. For instance, when rules $(\boldsymbol{R}_1, \boldsymbol{R}_2, \boldsymbol{R}_5, \boldsymbol{R}_9)$ are applied in sequence it results in a DAPD architecture ending with $\mathcal{P} = 82$ W and $\boldsymbol{B} = -18$ dB. This does not violate the transition constraints ℓ_1 and ℓ_2 during the derivation process. Similarly, the rule sequence $(\boldsymbol{R}_1, \boldsymbol{R}_2, \boldsymbol{R}_3, \boldsymbol{R}_5, \boldsymbol{R}_7, \boldsymbol{R}_9)$ results in a DADAPPD architecture.

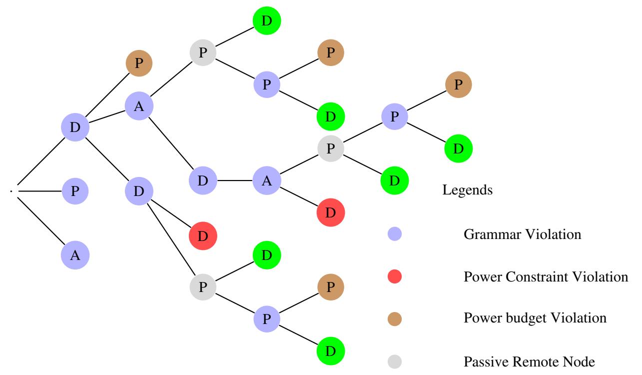


Fig. 9. Snapshot of word tree showing different architectures for scenario studied.

There are three choices at the root node: adding P or A or D to the word. A word starting with either P or A is rejected by the grammar (highlighted in blue). These words cannot be expanded as any addition to these words will also result in invalid words. Similarly, the grammar rejects words ending with P or A (such as DA and DP), highlighted in gray (e.g., passive RN). The feasible words are highlighted in green.

The word starting with DDD corresponds to one EN (E_0) connected to an ONU (S_0). This ONU forwards traffic to the central office through another ONU (S_0). The architecture equivalent of this word will consume more power than the reference PON architecture (represented by the word DDPD). This network path will consume 2 W more than PON architecture $A0$. So this does not meet the power constraint (highlighted in red). Similarly, the word DADAD is incomplete, and at this stage it needs at least one more A added to the word to meet the grammar. Thus, it must have at least four more power-consuming pieces of equipment than the reference PON architecture before the passive RN (not encountered yet). Computing the power consumption, this would exceed the power consumption of the reference PON architecture (assuming each piece of equipment consumes at least 0.5 W). So it does not meet the power constraint.

The words starting with DP cannot be realized since a MC (SE) cannot be passive and hence cannot meet the power margin (highlighted in brown). Similarly, the word starting with DAPPP fails to meet the power margin constraint. Two passive couplers (C_2) at the central office in front of the COE will reduce the SNR at −18 dB by 2 dB. This will be below the receiver sensitivity limit (−20 dB) even for small optical fiber lengths. For a similar reason, the word DADAPPP is not considered feasible.

Thus, for the given sample deployment parameters, architectures represented by words DDPD, DDPPD, DAPD, DAPPD, DADAPD, and DADAPPD are found to be feasible. These architectures correspond to equipment variants $(E_0, S_0, \mathrm{RN}, C_0)$, $(E_0, S_0, \mathrm{RN}, C_2, C_0)$, $(E_1, S_1, \mathrm{RN}, C_0)$, $(E_1, S_0, \mathrm{RN}, C_2, C_0)$, $(E_1, S_2, E_2, S_2, \mathrm{RN}, C_0)$, and $(E_1, S_2, E_2, S_2, \mathrm{RN}, C_2, C_0)$ along the network path starting from EN and ending at COE, respectively. Architectures DDPD, DAPD, DAPPD, and DADAPD are, respectively, referred to as architectures $A0$, $A1$, $A2$, and $A3$ in this paper.

The network operation of architecture represented by DDPPD is the same as DDPD. Similarly, the network operation of architecture represented by DADAPPD is the same as DADAPD. The only difference between these architectures is having a passive C_2 at the central office in front of COE C_0. C_2 does not participate in data- or control-packet exchanges.

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