Energy-Efficient Software-Defined AWGR-Based PON Data Center Network

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Abstract
In this paper, we present our results on tackling the oversubscription issue in the inter-cell communication in the Arrayed Waveguide PON based data center architecture proposed in our recent work. We enhance the bandwidth allocation by introducing 2-tiers of AWGRs to facilitate multipath routing and energy-efficient utilisation of resources. We also employ a centralized Software Defined Network (SDN) control and management system to coordinate and arbitrate the channel access for communication through the OLT links with PONs via wavelength reconfiguration and energy-efficient grooming. A benchmarking study between the proposed SDN architecture against the decentralized conventional design shows that with the SDN enabled architecture, the power consumption can be decreased by up to 90% for typical average data rates while maintaining zero blocking.

Keywords: passive optical network (PON), data centre, energy efficiency, optimization, software defined network (SDN).

1. Introduction

The steadily increasing number of servers and the exponentially growing traffic inside data centers have triggered the need of high speed optical networking infrastructure inside data centers to efficiently serve the ever-increasing server to server traffic [1]. Studies have shown that network connectivity is becoming a bottleneck in the data center. More importantly improving the per server data rate can significantly reduce the number of servers needed and hence the overall data center power consumption and cost. Therefore PONs developed for residential networking are a natural contender, being both an optical networking approach that can provide high speed links, low cost and low power consumption and a proven scalable solution that can support hundreds of millions of users.

In our previous work we investigated energy efficiency for core networks with data centers and clouds [2-8]. In [9], we introduced five novel designs for PON deployment in future cloud data centers to handle intra- and inter-rack communications. In [10], we proposed an AWGR-based PON architecture and have shown that energy savings of 45% and 80% can be achieved compared to the Fat-Tree [11] and BCube [12] architectures, respectively. In [10], we have shown that the AWGR-based PON architecture can be scaled up efficiently to hundreds of thousands of servers. We have described different technologies relying only on passive devices to manage intra-rack communication such as Fiber Bragg Grating (FBG), passive star reflectors, and passive polymer optical backplane. We have also shown that multi-path routing for inter-rack communication within the PON cell can be managed through intermediate passive AWGRs.

In this paper, we further investigate the proposed AWGR PON architecture; we improve the design by introducing a centralized SDN controller to coordinate and arbitrate the channel access for energy-efficient communication through the OLT links for uplink and downlink transmissions. We also introduce 2-tiers of AWGRs for inter-cell communication via multiple OLT switches for the purpose of minimizing cell to cell oversubscription, and facilitating multi-path routing. We present the results of a Mixed Integer Linear Programming (MILP) model developed to minimize power consumption of the network through efficient utilization and selection of resources and paths.

The remainder of this paper is structured as follows: In Section 2, we describe our proposed SDN energy-efficient AWGRs based interconnection for inter-cell communication. In Section 3, we present and discuss our results for energy-efficient bandwidth allocation through our optimization model. Finally we conclude the paper in Section 4.

2. Overview on the Architecture of the SDN-based AWGR PON Data Center

In this section, we describe the architecture of our proposed inter-cell interconnection; relying mostly on PONs to facilitate inter-racks communication. For details on intra-cell communication and the PON cell architecture please refer to [10]. The design, depicted in Figure 1, shows a schematic of proposed upper level connectivity for inter-cell communication using only passive devices. For simplicity, we only show uplink connections from PON cells to the OLT switches. The design facilitates multi path routing and also enhances the bandwidth allocation mechanism by introducing 2-tiers of optical passive AWGRs for connectivity with multiple OLT switches instead of having each PON cell connected to a single OLT port (conventional design). This allows efficient utilization of resources in case of low activity in some PON cell by allowing servers at heavily loaded cells to join multiple OLT ports where resources are available. Depending on the activity ratio of servers in different PON cells, the PON protocol can reconfigure the network through SDN by retuning the servers' transceivers to distribute the load among different OLT ports. Alternatively the SDN can assign resources and paths to consolidate loads at fewer PON cells to save power in response to the variation of the daily load. The main advantage of the design is its flexibility which allows servers to join different OLT switches based on availability of resources in order to reduce oversubscription and improve resources provisioning mechanism through energy efficient grooming.

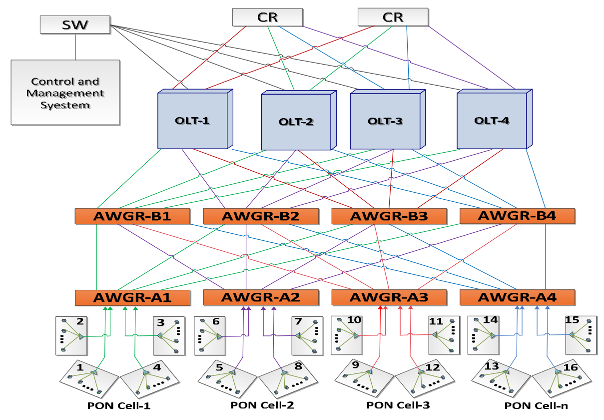

Figure.1 Upper-level connectivity for minimization of over subscription and efficient grooming

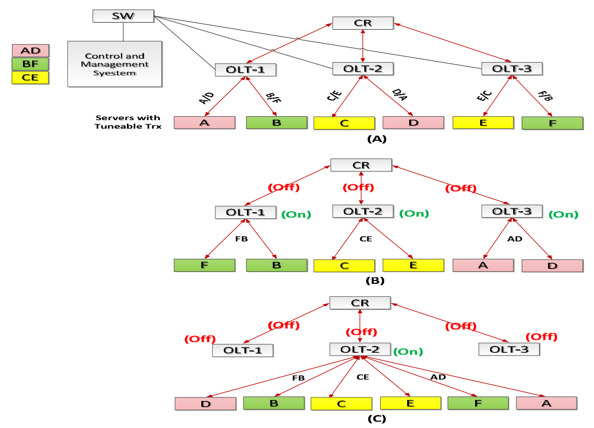

Figure.2 Energy-Efficient Bandwidth Allocation through reconfiguration and PON grouping

TABLE I. MILP OBTAINED WAVELENGTH ASSIGNMENTS FOR DOWNLINK CONNECTIONS FROM OLTS TO PONS

		OLT-1	OLT-2	OLT-3	OLT-4
PON Cell-1	PON-1	λ3	1	4	2
	PON-2	2	4	1	3
	PON-3	1	3	2	4
	PON-4	4	2	3	1
PON Cell-2	PON-5	2	1	4	3
	PON-6	1	2	3	4
	PON-7	3	4	1	2
	PON-8	4	3	2	1
PON Cell-3	PON-9	3	2	4	1
	PON-10	4	1	3	2
	PON-11	2	3	1	4
	PON-12	1	4	2	3
PON Cell-4	PON-13	3	4	2	1
	PON-14	1	2	4	3
	PON-14	2	1	3	4
	PON-16	4	3	1	2

TABLE II. MILP OBTAINED WAVELENGTH ASSIGNMENTS FOR UPLINK CONNECTIONS FROM PONS TO OLTS

		OLT-1	OLT-2	OLT-3	OLT-4
PON Cell-1	PON-1	4	3	2	1
	PON-2	1	2	3	4
	PON-3	3	4	1	2
	PON-4	2	1	4	3
PON Cell-2	PON-5	1	3	2	4
	PON-6	3	1	4	2
	PON-7	4	2	3	1
	PON-8	2	4	1	3
PON Cell-3	PON-9	4	1	2	3
	PON-10	2	3	4	1
	PON-11	1	4	3	2
	PON-12	3	2	1	4
PON Cell-4	PON-13	4	2	1	3
	PON-14	3	1	2	4
	PON-15	1	3	4	2
	PON-16	2	4	3	1

Tables I and II present the wavelength routing assignments obtained through MILP for uplink and downlink flows between OLTs and PONs for the network depicted in Figure 1. Having 4 PON cells with 4 PON groups each to connect with the 4 OLT switches will require each PON group in each PON cell to use 4 different wavelengths in order to reach the four OLT switches through the 2-tier AWGRs CLOS topology. The same wavelengths can be reused for all PON groups as each PON group is connected to a different port of the upper AWGR connected to the designated PON cell. The different 4 wavelengths from each PON group interfaced at the input of the lower AWGR at tier-1 will be directed to the different 4 output ports of the same AWGR. Each of the 4 wavelengths then will reach a different AWGR at tier-2 where it will be directed to a different OLT switch. Similarly other PON groups at the 4 different PON cells will route their wavelengths obeying the AWGRs property of wavelength routing. As a result, all PON groups in each PON cell shall reach all OLT switches using the four different wavelengths obeying the directionality and wavelength routing rules of the all AWGRs. The total number of wavelengths needed for uplink is 4 as the total number of OLT switches to be connected with is 4.

Figure 2 shows an example for a simplified schematic describing the role of the SDN in assigning paths and resources for nodes with demands. Assume the SDN has received requests to assign a route and resources for demands between the following pair of servers: (A, D), (B, F), and (C, E). Assume server A is located at PON Cell 1 in PON Group 1 where server D is located at PON Cell 2 in PON Group 5. Based on routing details and wavelengths assignment obtained from MILP and presented in Tables I and II, the scheduler assigns wavelength 2 for server A to join OLT-3 and OLT 3 uses wavelength 4 for downlink transmission. Therefore; servers A and D are grouped to join OLT-3. Similarly the demands for (B, F) and (C, E) are managed. In Figure 2(a) we have shown that servers are randomly assigned to OLTs and traffic is traversing multiple OLTs and CR. In Figure 2(b) we show that demanding servers can be grouped to a common OLT switch and in Figure 2(c) we show all demanding pairs can join a common OLT switch. Assignments depicted in Figure 2(c) allows for efficient use of resources and avoids routing through core switches and multiple OLT switches which further enhance power savings by switching off unused ports and devices.

3. Results

In this section we evaluate the power consumption of the network depicted in Figure 1. A model has been developed for energy-efficient bandwidth allocation to minimize total power consumption. The objective function of the optimization model aims to minimize total power consumption by minimizing total number of active OLT switches, OLT access ports, OLT uplink ports and core routers ports. The objective function is expressed as follows:

$$Minmize:$$
$$Total\ Power\ Consumption = \sum_{i=1}^{N}\left(P_{ch} + P_{SC} + \sum_{i=1}^{NAP} R_p \times P_r + \sum_{i=1}^{NUP} R_{up} \times P_{ur}\right) + \sum_{i=1}^{CR}\sum_{i=1}^{CP} R_{cp} \times P_{cp} \qquad (1)$$

Where P_{ch} and P_{SC} is the power consumption of the OLT chassis and switch fabric controller card respectively. N is the total number of OLT switches, NAP is the total number of OLT's access ports, R_p is the utilization of ports rate, P_r is the power consumption of the OLT port, NUP is total number of uplink ports in OLT switch, R_{up} is the utilization of the uplink port rate, P_{ur} is the power consumption of the uplink port, CR is the total number of core routers, CP is the total number of core routers ports, R_{cp} is the utilization of the core router port rate, and P_{cp} is the power consumption of the core router port.

The model ensures that uplink and downlink wavelengths capacity between PON groups and OLTs are not exceeded. Another capacity constraint for OLTs uplink with core routers is also introduced in the model. Flow conservation constraint is used to ensure that the flow going into a node is the same leaving it for all nodes except the source and destination. Also we ensure the AWGR directionality property is satisfied by ensuring flows are only directed from inputs to outputs of the AWGRs devices. Constraints are also used to ensure the rules of routing in AWGRs between inputs and outputs are satisfied. Table 1 shows the input parameters used in the model.

We compare two networks; a conventional decentralized network where each PON group connects to a single OLT switch and the second with a centralized control and management SDN as depicted in Figure 1. The SDN network allows any PON group to access any of the OLT switches through the introduced 2-tier of passive AWGRs by assigning the proper wavelength that a server with demand need to tune to. In the SDN design tuneable lasers need to be capable of tuning to additional wavelengths equals to the total number of OLTs. All demand requests are forwarded to the SDN controller through the OLTs via a commodity switch (SW) for assignment of transmission wavelengths and duration of transmission. Decisions made by the SDN are based on its global knowledge on the network parameters such as utilizations on uplink/downlink wavelengths between PONs and OLTs, active OLTs and core routers, utilization of ports in OLTs and core switches.

Our MILP results as presented in Figure 3 shows that with the SDN enabled architecture, the power consumption can be decreased by 65% to 90% compared to the decentralized conventional architecture for average data rate range between 250-2500 Mb/s following uniform distribution. This decrease is due to the efficient utilization of uplink and downlink resources between OLTs and PONs which reduces the number of OLT switches and access ports needed. Further energy savings are achieved by avoiding routing through multiple OLTs and core switches.

While in the conventional design, each PON cell is only connected to a single OLT switch, demand pairs for servers located in two different PON cells cannot be grouped to a single OLT and has to be forwarded to core routers which increases the overall power consumption as more core routers ports and OLTs uplink ports will be required. This increase in the traffic flow between OLTs and core routers will result in oversubscription for resources especially for the case with high data rates. Figure 4 demonstrates that with the conventional architecture, the blocking probability increases from 13% to 45% as data rates increase from 1Gb/s to 2.5Gb/s where in the SDN enabled network zero blocking is achieved for the evaluated data rates.

TABLE III: INPUT DATA FOR THE MODEL

Power consumption of Cisco ME4600 OLT Chassis	60 W [13]
Power consumption of Cisco ME4600 XCO Switch Fabric Card	180 W [13]
Power consumption of Cisco ME4600 AMX Access Card with 16 x GPON	90 W [13]
Cisco ME4600 UMX Uplink Card with 4 x 10GE	40 W [13]
Total GPON ports per OLT	256 [13]
GPON port uplink capacity	10Gb/s [13]
GPON port downlink capacity	10Gb/s [13]
Core router port capacity	10Gb/s
Power consumption of core router port	300 W [14]
Average demand rate following uniform distribution	250-2500 Mb/s

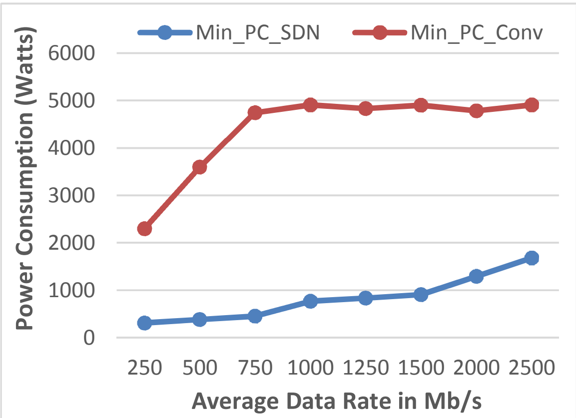

Figure.3 Power consumption evaluation for SDN over decentralized conventional networks

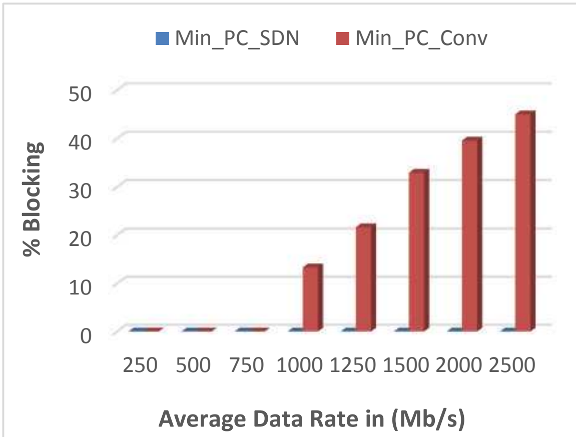

Figure.4 Blocking percentages of SDN minimized energy model against decentralized conventional network

4. Conclusions

This paper has proposed a SDN based AWGR PON data center interconnection design to provide energy efficient and highly elastic networking infrastructure to sustain the applications and services hosted by modern data centers. The design has shown that SDN can facilitate dynamic networks with wavelength configurability for efficient utilization and allocation of bandwidth resources. The proposed inter-cell fabric interconnection through the 2-tiers of AWGRs has improved the design by reducing oversubscription ratios and provisioning multi-path routing. A benchmarking study between the proposed SDN architecture against the decentralized conventional design shows that with the SDN enabled architecture, the power consumption can be decreased by up to 90% for typical average data rates while maintaining zero blocking.

Acknowledgments

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