Energy-Efficient VM Placement in PON-based Data Center Architectures with Cascaded AWGRs

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Abstract—Data centers based on Passive Optical Networks (PONs) can offer scalability, low cost and high energy-efficiency. Application in data centers can use Virtual Machines (VMs) to provide efficient utilization of the physical resources. This paper investigates the impact of VM placement on the energy-efficiency in a PON-based data center architecture that utilizes cascaded Arrayed Waveguide Grating Routers (AWGRs). In this paper, we develop a Mixed Integer Linear Programming (MILP) optimization model to optimize the VM placement in the proposed PON-based data center architecture. This optimization aims to minimize the power consumption of the networking and computing by placing the VMs and their demands in the optimum number of resources (i.e., servers and networking devices) in the data center. To date, we consider three objective functions in our optimization framework: 1) an objective function that serves the VM requests randomly, 2) an objective function that only minimizes the processing power consumption, and 3) an objective function that jointly minimizes processing and networking power consumption. The results showed that the total power consumption can be reduced by up to 50% when performing the joint minimization of processing and networking power consumption compared to the random VM allocation approach. In addition, a reduction in the networking power consumption by up to 74% can be achieved when performing joint minimization of processing and networking power consumption compared to considering the minimization of the processing power consumption only.

Keywords—Passive Optical Network (PON), Virtual Machines (VM), Data Center, Energy Efficiency, Arrayed Waveguide Grating Routers (AWGRs).

I. INTRODUCTION

Traditional data centre architectures have faced many challenges and limitations for example, low throughput, high latency, limited scalability, management complexity and high cost [1], [2]. Several studies have focused on introducing new energy-efficient designs for the Data Center Networks (DCNs) [3]-[17]. In addition, the growth in the Internet and its applications resulted in an increase in the volume of data that is typically transported over several network domains. This also increased the need for more energy-efficient data centres as the increasing data rates are leading to increase in the number of power hungry devices (i.e. access, aggregation and core electronic switches) within data centers [5], [18]. Several studies developed new architectures that provide solutions for more energy efficient, scalable and reliable data center designs [13], [19], [20].

Among those proposals, different researchers have introduced new designs that replace the power hungry devices by passive components (i.e. couplers and arrayed waveguide grating routers (AWGRs) which offer better power efficiency, lower cost and flexiblility in the resource utilization [1]. Using different passive devices, several passive optical network (PON) technologies were proposed for use in modern data centres to provide high performance, energy efficiency, scalability, high capacity and low cost [21].

Virtualization plays an important role in achieving efficient provisioning of physical resource and power saving for data centers. Virtualisation is mostly needed in environments that share resources (i.e. CPU processing and memory) among multiple applications by using a single physical system. According to [22], the computing capacity of data centers is on average 30% utilized. The 70% of the under utilized resources lead to massive power wastage while keeping the servers running in data centers. Therefore, the under-utilization of the resources of current data centre design is one of the most important challenges. One cause for this is the use of non-energy-efficient resource assignment algorithms where use is not made of resource consolidation. Resource consolidation can be achieved for example via packing VMs in the fewest number of servers and hence switching off a larger number of servers that are now freed.

In this paper, we develop a Mixed Integer Linear Programming (MILP) model to minimize the power consumption by optimizing the VM placement in the PON-based data center architecture we proposed in [23]. This architecture utilizes cascaded AWGRs to increase the scalability and provides multipath routing for PON-based architectures that use a single layer of AWGRs [12]. Also, our previous proposal improves the load balancing of traffic and reduces the oversubscription ratio by using four OLT switches rather than using a single OLT. In addition, this work proposes a design that enables intra-cell communication in the considered data center architecture by employing special
servers to forward the traffic of the servers within the cell which improves the scalability of the architecture and allows an increased number of racks per cell.

The reminder of this paper is organized as follows: Section II describes the system model for VM placement in the cascaded-AWGRs PON data center architecture. Section III explains the proposed MILP model for optimizing the energy-aware routing and VM placement. Section IV provides the optimization results and their discussions. Finally, Section V provides the conclusions and future work.

II. VM PLACEMENT IN THE PROPOSED DATA CENTER ARCHITECTURE

The connection of the two levels of AWGRs we proposed in [23] are shown in Fig. 1. We proposed using two levels of AWGRs to achieve full and diverse connectivity between the data centre processing cells and between processing cells and OLT switches. This provides flexibility and can enable load balancing in the architecture. In this work, we focus on the optimizing the VM placement in this architecture and its impact on improving the energy efficiency. Our previous work in [23] illustrated more details about the WDM wavelength assignment in the architecture. For inter cell communication, four cells and four OLT switches were considered that were linked through the PON depicted in Fig. 1. For intra cell communication, each cell contains four racks linked by employing a special server (relay server) as shown in Fig. 2. An arrayed waveguide (AWG) multiplexer is used to link the cell to the higher layer AWGRs as shown in Fig. 1 and in Fig. 2. In addition, Fig. 2 shows that the intra-rack communication is achieved by employing passive polymer optical backplane [24].
In this section, we briefly describe the Mixed Integer Linear Programming (MILP) model we developed for Energy-Aware VM placement in the cascaded-AWGRs based architecture. Three objectives have been considered, the first is to maximize the number of VM requests being served without the consideration of the power consumption (i.e. random allocation). The second is to minimize the power consumption of the processing servers, while the third objective is to jointly minimize the power consumption of the processing servers in addition to the networking power consumption of the special servers and their ONUs.

The sets, parameters, and variable used in the model are as follows:

**Sets and Parameters:**
- \( N \) Set of all nodes in the architecture
- \( N_m \) Set of neighboring nodes of node \( m \); \( m \in N \)
- \( S \) Set of Servers, where \( S \subseteq N \)
- \( SR \) Set of special servers, where \( SR \subseteq N \)
- \( T_{D_{vo}} \) Traffic demand between VMs \( v \) and \( o \), where \( v, o \in V \)

**Variables:**
- \( T_{R_{sd}} \) Traffic demand between server \( s \) and server \( d \) resulting from aggregating the traffic of all VMs placed in server \( s \), where \( (s, d) \in S \)
- \( \beta_{mn} \) Traffic demand between server \( (s, d), s, d \in S \), traversing through physical link \( (m, n) \), in the architecture, where \( m \in N \) and \( n \in N_m \)
- \( T_{TR_s} \) Total traffic forwarded by server \( s \), where \( s \in S \)
- \( \theta_s \) The power consumption of server \( s \), \( s \in S \)
- \( \mu_r \) The power consumption of a special server (relay server) \( r, r \in S \)
- \( \alpha_r \) Power consumption of ONUs connected to the special server \( r, r \in S \)
- \( SQR_{vs} \) Is a variable that is equal to 1 \((SQR_{vs} = 1)\) if request \( v; v \in V \) is served by server \( s; s \in S \), and otherwise is equal to zero.
- \( ADR_{voad} \) Is the product of \( SQR_{vs} \) and \( SQR_{sd} \) and is equal to 1 \((ADR_{voad} = 1)\) if VMs \( v \) and \( o; v, o \in V \), are assigned to the different servers \( s \) and \( d; s, d \in S \), and otherwise is equal to zero.

The MILP model optimizes VM allocation to the servers in the architecture under one of the following three objectives:

**Maximize:**
1. Random VMs allocation through maximizing the following cost function:
   \[
   \sum_{v \in V} \sum_{s \in S} SQR_{vs} \quad (1)
   \]

**Minimize:**
2. The processing servers power consumption \((PP)\):
   \[
   PP = \sum_{s \in S} \theta_s \quad (2)
   \]

Where, the total processing servers' power consumption \((PP)\) is composed of the power consumption of physical servers \((\theta_s)\) which are calculated by considering the idle power consumption of this server if it is activated, the proportional power that increases linearly with the VM workload, and the power consumption of the transceiver.
Minimize:

3. The total processing servers and networking power consumption (PP & NP):

\[ \text{PP & NP} = \sum_{s \in S} \theta_s + \sum_{r \in R} \mu_r + \sum_{r \in R} \alpha_r \] (3)

Where, the total power consumption of processing servers and networking equipment (PP & NP) is composed of the power consumption of physical servers (\( \theta_s \)), special servers (\( \mu_r \)) and ONUs attached to the special server (\( \alpha_r \)). The power consumption of physical servers (\( \theta_s \)) consists of the idle power consumption of this server if it is activated, the proportional power that increases linearly with the VM workload, and the power consumption of the transceiver. Similarly, the power consumption of special servers (\( \mu_r \)) consists of the idle power consumption of the special server if it is activated, the proportional power consumption related to the total traffic they forward.

\textbf{Subject to the following constraints:}

1. Traffic and routing constraints:

Constraint (4) is used to calculate the total traffic between server pairs that result from VM processing.

\[ TR_{sd} = \sum_{a \in A} \sum_{m \in M_{sd}} T_{rd} ADT_{vmd} \] (4)

\( \forall s, d \in S : s \neq d \)

Constraint (5) expresses the wavelength continuity (i.e., the flow conservation law) which guarantees that a flow entering into a node at a specific wavelength leaves the node at the same wavelength for all the nodes except for the destination and source nodes.

\[ \sum_{m_{emin}} \sum_{m_{emin}} \rho_{min} - \sum_{m_{emin}} \sum_{m_{emin}} \rho_{min} = \begin{cases} TR_{sd} & m = s \\ -TR_{sd} & m = d \\ 0 & \text{otherwise} \end{cases} \] (5)

\( \forall s, d \in S : s \neq d, \forall m \in M \)

Constraint (6) is used to calculate the total traffic transmitted by a server.

\[ TR_s = \sum_{d \in D} TR_{sd} \] (6)

\( \forall s \in S \)

2. Capacity constraints: We utilized a number of capacity constraints to ensure that the total traffic of a server is within its data rate range, the traffic forwarded by a special server does not exceed the ONU data rate, and that the traffic in each link does not exceed its capacity. In addition, we used capacity constraints to ensure that the demands of the VMs assigned to a server do not exceed its capacity.

\textbf{IV. RESULTS AND DISCUSSIONS}

Table I illustrates the input parameters used for the model. The CPLEX solver was used over a server with an Intel Core Intel(R) Xeon(R) CPU E5-1650 v2, running at 3.50 GHz, with 64.0 GB RAM which used to solve the MILP model. The model was run while considering different types of VMs requests, processing and memory requirements that were assumed to be uniformly and randomly distributed in this model. In addition, The traffic demand of VMs is uniformly and randomly distributed between 0.1Gb/s and 2.7Gb/s as shown in Table I. Moreover, each VM is assumed to communicate with 1 – 3 other VMs. The total number of VM requests evaluated in this work are 7, 14, and 21.

Fig.3 and Fig.4 compare the total power consumption of the three objective functions under different VM test cases. The objective functions are the random VM allocation, minimizing the processing power consumption (PP) and minimizing both processing and networking power consumption (PP & PN). The objective of the random VM allocation aims to maximize the number of VMs being served and is oblivious to the amount of power consumed by processing and networking layers. With the PP objective, the model minimizes the power consumption of the processing servers only by finding the optimal location to place the VMs and this does not take into account the networking power consumption in the architecture. Finally, the PP & NP objective performs the joint minimization of the power consumption of the processing and networking aims to reduce the overall power consumption.

![Fig. 3: Total power consumption of different number of VMs under the three objectives.](image)

| Parameter | Value |
|-----------|-------|
| Server’s or special server’s maximum power consumption. | 301 W [24] |
| Server’s or special server’s idle power consumption. | 201 W [24] |
| Server’s or special server’s portion of the processing capacity used for forwarding one request. | 5% |
| Processing capacity of the server. | 6.8 k – 10.8 k (MIPS) |
| Processing capacity of the special server. | 17.2 k (MIPS) |
| Memory capacity (RAM) of the server. | 8 – 50 (GB) |
| Data rate of servers. | 10 Gbps |
| Power consumption of ONU. | 2.5 W [26] |
| Data rate of ONU. | 10 Gbps |
| VM’s processing demand. | random and uniformly distributed between 1.6 k – 10 k (MIPS). |
| VM’s memory demand. | random and uniformly distributed. |
| Traffic demand between VMs | Random and uniformly distributed between 0.1 – 2.7 (Gbps). |
| Physical link capacity. | 140 Gbps |
| Number of servers Permitted to serve a VM request. | 1 |
| Power consumption of server transceiver. | 1 W |

The total power consumption results are illustrated in Fig.3 for the different objectives when considering three
different number of VMs (7, 14, and 21). The objective of minimizing the power consumption of the processing and special servers (i.e., PP & NP) reduced the power consumption by up to 50%, 44% and 30% compared to the random VM allocation. Moreover, the total power consumption under the PP & NP objective is reduced by 16%, 25% and 6% compared to the PP objective for 7, 14 and 21 VMs, respectively.

The networking power consumption is illustrated in Fig. 4 for the different objectives when optimizing the allocation of three different number of VMs (7, 14, 21). The networking power consumption, under the objective of minimizing the processing and relay servers power consumption (i.e., PP & NP), is reduced by up to 76%, 75% and 31% compared to the random VM allocation for the evaluated 7, 14 and 21 VMs, respectively. In addition, the objective of minimizing the power consumption of the processing and special servers (i.e., PP & NP) saved the power consumption by 8%, 74% and 23% compared to the objective of minimizing the processing servers power consumption only (i.e., PP). This results show that the MILP model tries to consolidate the VMs as much as possible using the least number of servers to avoid the increase in the inter VMs traffic flow between the servers. This in turn, reduces the power consumption of the networking devices (i.e., the special servers and the ONU attached to it).

![Fig. 4: Networking power consumption of different number of VMs under three objectives](image)

![Fig. 5: Processing power consumption of 7 VMs under two objectives with different average processing](image)

![Fig. 6: Networking power consumption of 7 VMs under two objectives with different average processing](image)

We then examined the impact of increasing the demand of VMs’ CPU on the power consumption under the PP and PP & NP objectives for 7 VMs. In this scenario, the processing capacity of the processing servers was assumed to be 6.8 k MIPS (Mega instructions per second), 8.8 k MIPS and 10.8 k MIPS. Figs. 5, 6 and 7 show the power consumption results for each value of the processing capacity for the two considered objectives. As shown in Fig. 5, the power consumption increases as the CPU demands of the VMs increase. This results as a consequence of increases in the number of active physical servers that are needed to accommodate the VMs demand. Moreover, the lowest value of the processing power consumption as shown in Fig. 5 appears clearly at the highest value of servers’ capacity as higher capacity leads to serving more VMs in fewer servers. In comparison as shown Fig. 5, the processing power consumption under the two objectives is comparable as the average VMs demand processed is 1.6 k MIPS. As a results, the VMs were consolidated into less number of servers which lead to lower networking power consumption. As shown in Fig. 6, with the objective of minimizing the processing and special servers (PP & NP) power consumption, a reduction in the networking power consumption of up to 75% was achieved compared to the objective of minimizing the processing power consumption (PP) only. The reason behind the reduction in the networking power consumption were the VMs better packing into servers which leads to reduce inter-server traffic.

Furthermore, The total power consumption of both objectives is presented in Fig. 7. As can be seen, the power savings in the objective of minimizing the processing and special servers power consumption for processing 7 VMs is up to 33%. This can be associated with the ability of the model to pack VMs into fewer servers which lowers the inter server traffic and leads to a reduction in the number of active networking devices.

![Fig. 7: Total power consumption of 7 VMs under two objectives with different average processing](image)

V. CONCLUSIONS

This paper introduced a MILP model to minimize the power consumption in a cascaded-AWGRs PON data center architecture by optimizing VMs placement. We considered three objective functions. The first is to perform a random
allocation of VMs. The second is to reduce the power consumption of the processing servers that host VMs and the third is to reduce the power consumption of the processing servers in addition to the power consumption of the special server that is equipped with an ONU for the inter cell communication. The power consumption under the three objectives was tested under different number of VMs (7, 14, and 21).

The results showed that with the , PP & NP approach, the total power consumption can be reduced by up to 50%, 44% and 30% compared to the objective of random VM allocation for the evaluated 7, 14 and 21 VMs, respectively. Moreover, the findings showed that the total power consumption under the objective of minimizing the power consumption at the processing and networking level (PP & NP) was reduced by 16%, 25% and 6% compared to the objective of minimizing the power consumption at the processing level only (PP) for the evaluated 7, 14 and 21 VMs, respectively. In addition, we considered the impact of increasing the processing demand for VMs and the capacity of the servers on the total power consumption, processing power consumption and networking power consumption. The results showed that the networking power consumption (i.e., be reduced by up to 75%) when minimizing the total (i.e., processing and networking) power consumption compared to minimizing of the processing power consumption only. In future work, designing heuristic algorithms is planned that mimic MILP model and provides optimal VM placement to execute in a real-time.

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REFERENCES

[1] C. Kachris and I. Tomkos, "Power consumption evaluation of hybrid WDM PON networks for data centers," in 2011 16th European Conference on Networks and Optical Communications, 2011, pp. 118-121: IEEE.

[2] A. E. Eltraify, M. O. Musa, and J. M. Elmirghani, "TD-WDM over AWGR based passive optical network data centre architecture," in 2019 21st International Conference on Transparent Optical Networks (ICTON), 2019, pp. 1-5: IEEE.

[3] Z. T. Al-Azez, A. Q. Lawey, T. E. El-Gorashi, and J. M. Elmirghani, "Virtualization framework for energy efficient IoT networks," in 2015 IEEE 4th International Conference on Cloud Networking (CloudNet), 2015, pp. 74-77: IEEE.

[4] H. M. M. Ali, A. Q. Lawey, T. E. El-Gorashi, and J. M. Elmirghani, "Energy efficient disaggregated servers for future data centers," in 2015 20th European Conference on Networks and Optical Communications (NOC), 2015, pp. 1-6: IEEE.

[5] X. Dong, T. E. El-Gorashi, and J. M. Elmirghani, "Green IP over WDM networks with data centers," Journal of Lightwave Technology, vol. 29, no. 12, pp. 1861-1880, 2011.

[6] X. Dong, T. E. El-Gorashi, and J. M. Elmirghani, "Energy-efficient IP over WDM networks with data centers," in 2011 13th International Conference on Transparent Optical Networks, 2011, pp. 1-8: IEEE.

[7] X. Dong, T. E. El-Gorashi, and J. M. Elmirghani, "Use of renewable energy in an IP over WDM network with data centers," IET optoelectronics, vol. 6, no. 4, pp. 155-164, 2012.

[8] X. Dong, T. E. El-Gorashi, and J. M. Elmirghani, "Joint optimization of power, electricity cost and delay in IP over WDM networks," in 2013 IEEE International Conference on Communications (ICC), 2013, pp. 2370-2375: IEEE.

[9] X. Dong, T. E. El-Gorashi, and J. M. Elmirghani, "On the energy efficiency of physical topology design for IP over WDM networks," Journal of Lightwave Technology, vol. 30, no. 12, pp. 1931-1942, 2012.

[10] A. Q. Lawey, T. E. El-Gorashi, and J. M. Elmirghani, "Energy efficient virtual network embedding for cloud networks," Journal of Lightwave Technology, vol. 33, no. 9, pp. 1828-1849, 2014.

[11] L. Nondo, T. E. El-Gorashi, and J. M. Elmirghani, "Energy efficient network embedding for cloud networks," Journal of Lightwave Technology, vol. 33, no. 9, pp. 1828-1849, 2014.

[12] A. Hammadi, T. E. El-Gorashi, and J. M. Elmirghani, "High performance AWGR PONs in data center networks," in 2015 17th International Conference on Transparent Optical Networks (ICTON), 2015, pp. 1-5: IEEE.

[13] A. Hammadi, T. E. El-Gorashi, M. O. Musa, and J. M. Elmirghani, "Server-centric PON data center architecture," in 2016 18th International Conference on Transparent Optical Networks (ICTON), 2016, pp. 1-4: IEEE.

[14] O. Z. Alsulami, M. O. Musa, M. T. Alsheheedi, and J. M. Elmirghani, "Visible light optical data centre links," in 2019 21st International Conference on Transparent Optical Networks (ICTON), 2019, pp. 1-5: IEEE.

[15] A. E. Eltraify, M. O. Musa, A. Al-Quzweeni, and J. M. Elmirghani, "Experimental evaluation of passive optical network based data center architecture," in 2018 20th International Conference on Transparent Optical Networks (ICTON), 2018, pp. 1-4: IEEE.

[16] A. E. Eltraify, M. O. Musa, A. Al-Quzweeni, and J. M. Elmirghani, "Experimental Evaluation of Server Centric Passive Optical Network Based Data Centre Architecture," in 2019 21st International Conference on Transparent Optical Networks (ICTON), 2019, pp. 1-5: IEEE.

[17] J. Elmirghani, T. El-Gorashi, and A. Hammadi, "Passive optical-based data center networks," University of Leeds, U.S. Patent 10,498,450, issued December 3, 2019.

[18] X. Dong, T. E. El-Gorashi, and J. M. J. J. O. L. T. Elmirghani, "IP over WDM networks employing renewable energy sources," vol. 29, no. 1, pp. 3-14, 2011.

[19] J. Beals et al., "A terabit capacity passive polymer optical backplane based on a novel meshed waveguide architecture," vol. 95, no. 4, pp. 983-988, 2009. based on a novel meshed waveguide architecture," Applied Physics A, vol. 95, pp. 983-988, 2009.

[20] A. A. Hammadi, "Future PON data center networks," University of Leeds, School of Electronic and Electrical Engineering, Aug. 2016.

[21] Jun-ichi Kani, "Enabling technologies for future scalable and flexible WDM-PON and WDM/TDM-PON systems," IEEE Journal of Selected Topics in Quantum Electronics, vol. 16, no. 5, pp. 1290-1297, 2010.

[22] I. X. P. H. Processor. (2022, 21/08/2021). 3rd Generation Intel® Xeon® Processor. 24-75m Cache-3.10-4.50Ghz/specifications.html?wapkw=8354H

[23] M. Alharthi, S. H. Mohamed, B. Yousef, T. E. El-Gorashi, and J. M. J. a. p. a. Elmirghani, "Optimized Passive Optical Networks with Cascaded-AWGRs for Data Centers," 2021.

[24] A. Hammadi, M. Musa, T. E. El-Gorashi, and J. H. Elmirghani, "Resource provisioning for cloud PON AWGR-based data center architecture," in 2016 21st European Conference on Networks and Optical Communications (NOC), 2016, pp. 178-182: IEEE.

[25] I. X. P. H. Processor. (2022, 21/08/2021). 3rd Generation Intel® Xeon® Scalable Processors. Available: https://www.intel.com/content/www/us/en/products/server/8thgen-8354h-processor-24-75m-cache-3.10-4.50Ghz/specifications.html?wapkw=8354H

[26] K. Grobe, M. Roppelt, A. Autenrieth, J.-P. Elbers, and M. J. L. C. M. Eiselt, "Cost and energy consumption analysis of advanced WDM-PONs," vol. 49, no. 2, pp. 452-462, 2011.