Energy Minimized Federated Fog Computing over Passive Optical Networks

Abdullah M. Alqahtani, Barzan Yosuf, Sanaa H. Mohamed,Taisir E.H. El-Gorashi, and Jaafar M.H. Elmirghani, Fellow, IEEE

School of Electronic and Electrical Engineering, University of Leeds, LS2 9JT, United Kingdom

Abstract— **The rapid growth of time-sensitive applications and services has driven enhancements to computing infrastructures. The main challenge that needs addressing for these applications is the optimal placement of the end-users' demands to reduce the total power consumption and delay. One of the widely adopted paradigms to address such a challenge is fog computing. Placing fog units close to end-users at the edge of the network can help mitigate some of the latency and energy efficiency issues. Compared to the traditional hyperscale cloud data centres, fog computing units are constrained by computational power, hence, the capacity of fog units plays a critical role in meeting the stringent demands of the end-users due to intensive processing workloads. In this paper, we first propose a federated fog computing architecture where multiple distributed fog cells collaborate in serving users. These fog cells are connected through dedicated Passive Optical Network (PON) connections. We then aim to optimize the placement of virtual machines (VMs) demands originating from the end-users by formulating a Mixed Integer Linear Programming (MILP) model to minimize the total power consumption. The results show an increase in processing capacity and a reduction in the power consumption by up to 26% compared to a Non-Federated fogs computing architecture.**

Keywords— Fog Computing, Energy Efficiency, resource allocation, Internet of Things (IoT), Mixed Integer Linear Programming (MILP), optimization, Passive Optical Networks (PONs).

I. INTRODUCTION

The growth in next generation applications is accelerated by the Internet of Things (IoT), smart cities, healthcare, and smart grids to name a few. This is expected to result in the generation of enormous volumes of data that is usually transported over multiple network domains towards remote cloud data centers for processing purposes. Processing all that data at the cloud will cause further bottlenecks in the already congested core networks and hence, this will have a detrimental impact on latency and energy efficiency. Alternatively, through the concept of fog computing, computational resources are placed close to end-users, at the edge of the network, in order to extend the capabilities of cloud data centers. Fog computing units could be any device that can feature compute and processing capability such as routers, switches, accesses points or small racks of servers [1]–[8]. However, the processing capacity of fog units is limited compared to the cloud. Which will often result in congestion or virtual machine (VM) request blockage under high demands. Therefore, the capacity of fog computing units should be addressed to ensure that they are well-suited to the demands of time-sensitive applications [9]–[11].

The authors in [9] optimized the service allocation problem using an integer programming model in a cloud-fog architecture. The goal of the work is to minimize the latency experienced by IoT services while meeting resource constraints. Two modes of service allocation are considered which the authors refer to as serial and parallel allocation. With the former, higher delays are experienced by the services, whilst with the latter approach, lower service delays are observed. The study in [10] reported on the work of a consortium called RECAP that aims to advance cloud and edge technologies to develop mechanisms for reliable capacity provisioning as well as making application placement and infrastructure orchestration autonomous, predictable and optimized. This automation is achieved by intelligent profiling of workloads.

Passive Optical Networks (PONs) are widely utilized as an optimal technology in the access part of the network as well as the cloud domain due to their energy efficiency and high bandwidths that are particularly suited to high bit-rate applications such as streaming, Video on Demand (VoD) and cloud gaming, etc. [12]–[15]. The authors in [15] assessed wired and wireless network infrastructures in terms of their applicability to real-time applications. The study in [15] shows that PON is a power efficient access technology due to passive nodes, with the additional advantage of abundant bandwidth.

The work in [16] studied the performance of multiple cooperative fog servers in a wireless network by evaluating the users' quality of experience (QoE) and fog nodes' power efficiency. The trade-off between these two metrics are discussed for a single-node fog computing network as well as extending the study to look at fog node cooperation. The study comprises of a workload allocation problem that is solved through a distributed optimization algorithm, which achieved comparable results to the results obtained by their global optimization model. Moreover, the authors in [17] focused on minimizing the total service latency of multiple users with homogenous tasks. Their fog radio access network (F-RAN) model utilized the existing wireless infrastructure such as small cells and near-range communication links at the edge layer.

Different from the aforementioned studies, in this paper we propose an energy efficient fog computing architecture that realizes a federated fog approach in which fog cells are connected through a dedicated PON and where neighbouring fog cells can collaborate in processing intensive demands. We then optimize and evaluate the energy efficiency of this architecture compared to a Non-Federated architecture by utilizing a Mixed Integer Linear Programming (MILP) model that optimizes the placement of Virtual Machines (VMs) requested by end-users while aiming to reduce the total networking and processing power consumption. We benefit from our previous work in energy efficiency that tackled areas such as distributed processing in the IoT/Fog [18]–[21], green core and data centre (DC) networks [22]–[31] ,[32]–[37],
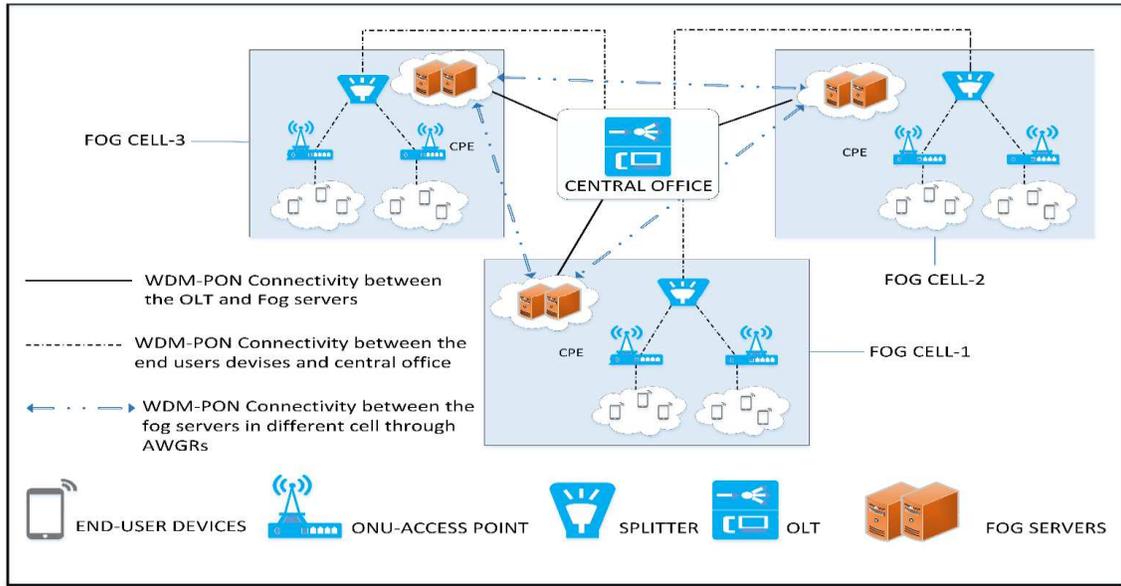
Fig. 1. The Federated Fog Architecture over a Passive Optical Network (PON).

network virtualization and service embedding in core and IoT networks [38]–[41] and machine learning and network optimization for healthcare systems [42]–[45] and network coding in the core network [46], [47].

The reminder of this paper is organized as follows: Section 2 explains the proposed architecture and the optimization model. Section 3 presents and discusses the optimization results. Finally, Section 4 concludes the paper and outlines avenues for future research.

II. THE PROPOSED PON-BASED FEDETARED FOG ARCHITECTURE

Time-sensitive applications should be processed in the nearest computing units close to the end-devices in order to meet the low-latency requirements of these applications[1]. However, due to the size of the collected data at the edge of the network, adaptions are needed in the computing architectures to tackle their limited capacity so that large amounts of data can be processed closer to the data sources. Therefore, the proposed fog based PON architecture provides connectivity between three (or more) fog computing cells. In a federated fog network, multiple fog cells are able to collaborate to host the user demands and this can subsequently reduce the total power consumption compared to a non-federated network with non-collaborative fog cells, as shown in Fig. 2. The proposed architecture, as shown in Fig. 1, is comprised of a networking layer and a processing layer. In the following, we elaborate these layers and provide the proposed MILP model to optimize the VMs placement in the PON-based Federated Fog architecture.

A. The Networking Layer

The networking layer is responsible for aggregating the data from the end-user's equipment and forwarding it to the processing units. As shown in Fig. 1, the networking layer is composed of energy efficient devices within the PON architecture that are comprised

of the Optical Networking Units (ONU), that represent the Customer Premises Equipment (CPE). These are in charge of collecting data from end-users. In addition, an Optical Line Terminal (OLT) at the Central Office, is in charge of collecting data from the ONUs, and a passive splitter between the ONUs and OLT. The OLT provides a point-to-multipoint fibre optical network. Each of the Fog cells is connected to the OLT. In addition, The Fog cells are interconnected via a Wavelength Division Multiplexing Passive Optical Network (WDM-PON) we proposed in [1]. The VM requests are initially assembled in the ONU-Access points, and then forwarded to the OLT. The non-Federated architecture on the other hand contains Fog cells that have no dedicated interconnections as can be seen in Fig. 2.

B. The Processing Layer

The processing layer is responsible for hosting the virtual machines requests (VMs) generated from the end-user's devices and processing the data in efficient ways to meet the delay sensitive applications requirements. In the proposed architecture, the processing layer is comprised of fog servers, where each fog cell has multiple fog servers. Each server is equipped with an ONU device. The OLT optimally allocate the VMs requests to the appropriate fog servers based on the available capacity and the power consumption via WDM-PON.
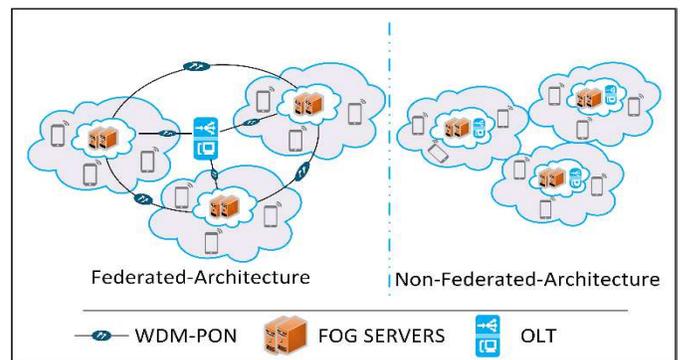
Fig. 2. PON-Based Federated Fog vs. PON-Based Non-Federated Fog.

Moreover, the servers within different cells, as shown in Fig. 1, are able of communicating with each other directly via the passive PON component which is Arrayed waveguide grating Routers (AWGRs) to avoid consuming more power by communicating via OLT as explained in our previous work [1].

C. MILP Optmization Model

The proposed MILP model aims to optimize the placement of VM demands and augment the capacity of fog cells in the proposed architecture with the objective of minimizing the total power consumption jointly with minimizing the number of blocked VMs. The model optimizes the allocation of demands among the neighbouring fog computing cells so that over-demanding VM requests on one of the fog cells can be processed in the closet connected available fog cell. Note that in the proposed federated fog architecture, there is PON connectivity between the fog cells to facilitate "borrowing" of data processing capabilities and all of the fog cells are connected to the OLT. On the other hand, there is no PON connectivity among fog cells in the non-federated fog architecture as each cell is connected to a dedicated OLT device, as shown in Fig. 2. The proposed MILP model minimizes the networking and processing power consumption of VM requests. Each VM request consists of a CPU processing demand which is the amount of processing required in Million Instructions Per Second (MIPS), the traffic demand which is the amount of data required in Gbps, and the RAM workload which is the amount of memory allocated to each VM request in MB.

The following notations are the sets, parameters and variables used in the optimization model:

1) Sets:

N	Set of all nodes in the proposed architecture
N_m	Set of all neighbouring nodes to node m in the proposed architecture
ONU_N	Set of ONUs in the networking layer, where $ONU_N \in N$
OLT_N	Set of OLTs in the networking layer, where $OLT_N \in N$
S_P	Set of servers in the processing layer, where $S_P \in N$
VMs	Set of all VM request

2) Networking Layer Parameters:

M_{ONU}	Maximum power consumption of ONUs.
I_{ONU}	Idle power consumption of ONUs.
B_{ONU}	Maximum data rate of ONUs.
E_{ONU}	Energy per bit of ONU, where $E_{ONU} = \left(\frac{M_{ONU} - I_{ONU}}{B_{ONU}}\right)$.
M_{OLT}	Maximum power consumption of OLTs.
I_{OLT}	Idle power consumption of OLTs.
B_{OLT}	Maximum data rate of OLTs.
E_{OLT}	Energy per bit of OLT port, where $E_{OLT} = \left(\frac{M_{OLT} - I_{OLT}}{B_{OLT}}\right)$.
C_{mn}	Capacity of the physical link (m,n), where m, n within N.

3) Processing Layer Parameters:

M_S	Maximum power consumption of servers
I_S	Idle power consumption of servers
C_S	CPU capacity of the servers
R_S	RAM memory capacity of the servers
O_S	The proportional power consumption of the servers, where $O_S = M_S - I_S$
P_d^{ONU}	Maximum power consumption of ONUs
D_d^{ONU}	Maximum data rate of ONUs
A_S	Number of servers permitted to serve one VM request

4) Virtual Machines Requests Parameters:

C_{VMs}	CPU demand of VM $s \in VM$ in MIPS.
R_{VMS}	RAM memory demand of VM $s \in VM$ in GB.
T_{VMs}	Traffic Demand of VM s, $s \in VM$ in Gbps.

5) Variables:

L_{sd}	Traffic demand between source node, where s∈VMs and processing device, where d∈S.
L_{sd}^{mn}	Traffic flow between source node s∈VMs and processing device d∈S, traversing node m∈N and n∈Nm.
P_{sd}	Processing demand between source node s∈VMs and processing device d∈S.
R_{sd}	RAM memory demand between source node s∈VMs and processing device d∈S.
L_m	Amount of traffic gathered by node m∈N.
B_m	B_m=1, if the networking node $m \in N$ is activated, otherwise B_m=0.
D_m	Defined as the AND of two variables B_m and L_m, $m \in N$.
B_d	B_d=1, if the server in the processing layer d∈ S_P is activated, otherwise B_d=0

The network layer's power consumption (NET_{PC}) is composed of the power consumption of ONU and OLT devices in the access network. Additionally, the processing power consumption (P_{PC}) is composed of the power consumption of the servers and ONU devices attached to each server. Note that the power consumption of the ONU devices is of two types: 1) the ONUs attached to processing servers which work as transceivers and have an on/off power consumption profile, 2) the ONUs used as Customer Premises Equipment (CPE). These have a linear power profile with a proportional and idle section [49].

The MILP model is defined as follows:

The objective: Minimize the total networking and processing power consumption of the proposed architecture[48]:

$$NET_{PC} + P_{PC} \tag{1}$$

Subject to the following constraints:

$$\sum_{\substack{n\in \text{Nm} \\ m\neq n}} L_{sd}^{mn} - \sum_{\substack{n\in \text{Nm} \\ m\neq n}} L_{sd}^{nm} = \begin{cases} L_{sd} & m = s \\ -L_{sd} & m = d \\ 0 & otherwise \end{cases} \quad (2)$$

$$\forall\ s\in \text{VMs}, d\in \text{S}, \forall\ m\in \text{N}$$

Equation (2) is a traffic flow conservation constraint to ensure that the traffic demand for each VM that enters a node leaves it at same level (except for the source and destination nodes).

$$\sum_{s\in VM_s} C_{VMs}\, P_{sd} \leq\ C_s \quad (3)$$

$$\forall\ d \in S$$

Equation (3) ensures that the processing capacity of the VMs' requests does not exceed the processing capacity of the allocated server.

III. MILP MODEL RESULT

In this section, we evaluate the efficiency of the Federated-Fog compared with the Non-Federated Fog over PON as shown in Fig. 2 under three different scenarios of VMs requests (i.e. 10, 15, and 20 VMs). This was performed with random uniform distribution for the CPU, memory and traffic demands as shown in Table 1. The VMs' processing requirements are uniformly distributed between (160k MIPS and 280k MIPS) in one cell, and (10k MIPS to 56k MIPS) in the other cells. This results in one fog cell being highly loaded. The VMs memory requirements are uniformly distributed between (100MB and 500MB) [49]. Moreover, The VMs' traffic demands are uniformly distributed between 1 Gbps and 10 Gbps. It is important to note that since the OLT is shared by many users and applications, the idle power consumption of this device should be divided among the applications running at a given point in time, i.e. only a fraction of the maximum idle power consumption is accounted for in the optimization model [48]. The input data used in the MILP model is presented in table 1.

TABLE I. INPUT DATA USED IN THE MODEL

Server's maximum power consumption [50].	457 W
Server's idle power consumption (66% of Maximum power) [50].	301 W
Processing capacity of the server [50].	280k MIPS
Processing capacity of the VMs.	10k MIPS - 280k MIPS
Memory capacity (RAM) of the server [50].	16 GB
Memory capacity (RAM) of the VMs [49].	100 MB - 500 MB
OLT Maximum power consumption [51].	1940 W
OLT idle power consumption (90% of Maximum power.	1746 W
OLT data rate [51].	8600 Gbps
ONU Maximum power consumption [52].	2.5 W
ONU idle power consumption (60% of Maximum power) [52].	1.5 W
ONU data rat e[52].	10 Gbps
VMs Traffic Demands [49].	1 Gbps – 5 Gbps
Capacity of Optical physical link [53].	32 wavelengths per fibre at 40 Gbps per wavelength

We have evaluated the server utilization of both architectures by comparing the number of VM requests processed versus the number of VM requests blocked. Fig. 3 shows that with the Non-Federated Fog approach, 3 VMs are blocked in total due to the limited local processing resources available to each fog cell. Fig. 4, on the other hand, shows that each cell in the Federated Fog architecture is capable of borrowing data processing from neighbouring fog cells, hence, no VMs are blocked with this approach. Moreover, we have compared the total power consumption of both approaches. As can be seen in Fig. 5, the power savings in the Federated Fog architecture for processing 10, 15 and 20 VMs is up to 26%, 7% and 2%, respectively. The processing power consumption required to accommodate the assigned VMs and the number of activated servers, as shown in Fig. 6 and Fig. 7 were the main contributing factors in the power savings. In the Federated Fog architecture, the model is able to pack servers and hence use fewer processing servers due to the federation facilitated by the PON connectivity. At 10 VMs, both approaches have processed the entire VMs demands, as shown in Fig. 3 and Fig. 4. However, as can be observed in Fig. 7, the difference is in the power consumed for processing in the VMs, as with the Non-Federated Fog, a higher number of servers were utilized as opposed to the Federated Fog approach. When considering the placement of 20 VMs, the Non-Federated Fog has used 7 servers to accommodate 18 VMs out of 20 VMs while the Federated Fog has used 6 servers to accommodate all of the VMs, as shown in Fig. 7. Obviously, due to the PON devices used in the networking layer, both architectures are highly energy efficient in networking power consumption and the processing power consumption has the greatest weight in terms of where to process the VMs, as shown in Fig. 6. The MILP model was developed using AMPL and solved with IBM's commercial solver CPLEX on a PC with 16 GB RAM and a core i5 CPU.
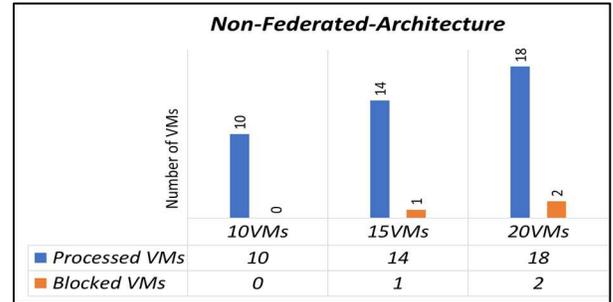
Fig. 3. Number of processed and blocked VMs.
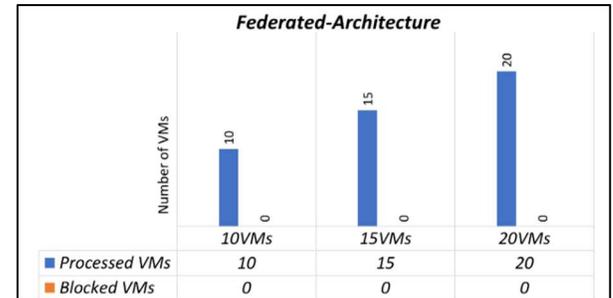
Fig. 4. Number of processed vs. blocked VM.
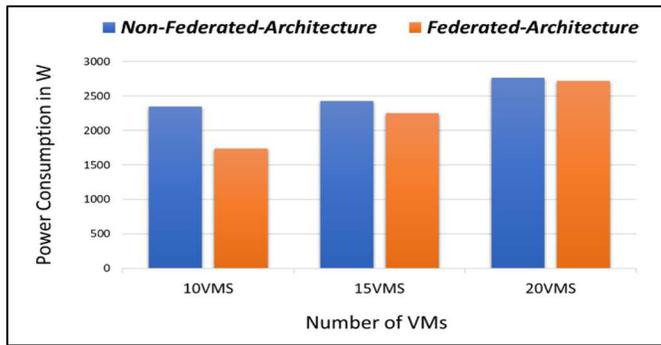
Fig. 5. Total power consumption of both fog architectures.
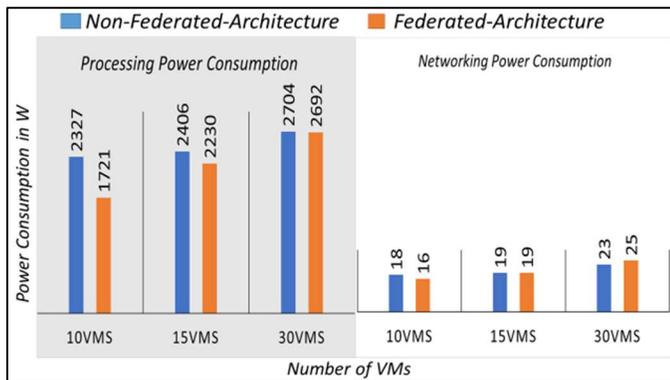
Fig. 6. Networking power consumption versus processing power consumption in both fog architectures.
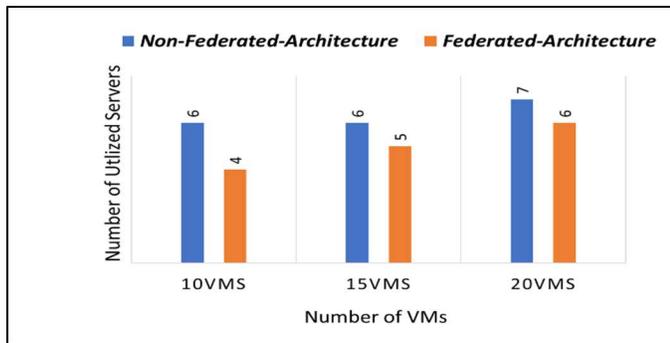
Fig. 7. Server utilization in both fog architectures.

IV. CONCLUSIONS

In this paper, we proposed a federated fog computing architecture with a number of fog computing units in the access network where fog cells are connected through a dedicated PON. This enables providing higher processing capacity in the fog layer that can process more data closer to end-users. We compared the Federated Fog approach to the Non-Federated Fog approach over a PON access network. The results showed that through the Federated approach, a total power saving of up to 26% can be achieved compared to the Non-Federated Fog approach. Moreover, the total number of VMs blocked can be reduced. Future work includes extending the optimization model to consider a weighted objective function that incorporates delay and power, mobility-aware workload assignment and implementing a prototype to assess the feasibility of the proposed architecture. Also, an interesting direction for future work is to consider different levels of resource efficiency in the networking and processing layers as there can be intrinsic trade-offs in this regard.

REFERENCES

[1] A. M. Alqahtani, S. H. Mohamed, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "PON-Based Connectivity for Fog Computing," in *2020 22nd International Conference on Transparent Optical Networks (ICTON)*, 2020, pp. 1–6.

[2] S. H. Mohamed, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Energy Efficiency of Server-Centric PON Data Center Architecture for Fog Computing," in *2018 20th International Conference on Transparent Optical Networks (ICTON)*, 2018, pp. 1–4.

[3] A. C. Baktir, A. Ozgovde, and C. Ersoy, "How Can Edge Computing Benefit From Software-Defined Networking: A Survey, Use Cases, and Future Directions," *IEEE Commun. Surv. Tutorials*, vol. 19, no. 4, pp. 2359–2391, 2017.

[4] M. Satyanarayanan, "The Emergence of Edge Computing," *Computer (Long. Beach. Calif)*., vol. 50, no. 1, pp. 30–39, 2017.

[5] K. Dolui and S. K. Datta, "Comparison of edge computing implementations: Fog computing, cloudlet and mobile edge computing," in *2017 Global Internet of Things Summit (GIoTS)*, 2017, pp. 1–6.

[6] S. Yi, Z. Hao, Z. Qin, and Q. Li, "Fog Computing: Platform and Applications," in *2015 Third IEEE Workshop on Hot Topics in Web Systems and Technologies (HotWeb)*, 2015, pp. 73–78.

[7] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, "Fog computing and its role in the internet of things," *Proc. first Ed. MCC Work. Mob. cloud Comput. - MCC '12*, p. 13, 2012.

[8] Cisco, "Fog Computing and the Internet of Things: Extend the Cloud to Where the Things Are," *WHITE PAPER*, 2015. [Online]. Available: https://www.cisco.com/c/dam/en_us/solutions/trends/iot/docs/computing-overview.pdf. [Accessed: 15-Dec-2019].

[9] V. B. C. Souza, W. Ramirez, X. Masip-Bruin, E. Marin-Tordera, G. Ren, and G. Tashakor, "Handling service allocation in combined Fog-cloud scenarios," in *2016 IEEE International Conference on Communications, ICC 2016*, 2016.

[10] P. O. Ostberg *et al.*, "Reliable capacity provisioning for distributed cloud/edge/fog computing applications," in *EuCNC 2017 - European Conference on Networks and Communications*, 2017.

[11] M. T. Thai, Y. D. Lin, Y. C. Lai, and H. T. Chien, "Workload and Capacity Optimization for Cloud-Edge Computing Systems with Vertical and Horizontal Offloading," *IEEE Trans. Netw. Serv. Manag.*, vol. 17, no. 1, pp. 227–238, Mar. 2020.

[12] S. H. Mohamed, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "On the energy efficiency of MapReduce shuffling operations in data centers," in *International Conference on Transparent Optical Networks*, 2017.

[13] A. A. Alahmadi, M. O. I. Musa, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Energy Efficient Resource Allocation in Vehicular Cloud based Architecture," in *21st International Conference on Transparent Optical Networks (ICTON)*, 2019, pp. 1–6.

[14] R. Alani, A. Hammadi, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "PON data centre design with AWGR and server based routing," in *2017 19th International Conference on Transparent Optical Networks (ICTON)*, 2017, pp. 1–4.

[15] J. Baliga, R. Ayre, K. Hinton, and R. S. Tucker, "Energy consumption in wired and wireless access networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 70–77, 2011.

[16] Y. Xiao and M. Krunz, "QoE and power efficiency tradeoff for fog computing networks with fog node cooperation," in *Proceedings - IEEE INFOCOM*, 2017.

[17] A. C. Pang, W. H. Chung, T. C. Chiu, and J. Zhang, "Latency-Driven Cooperative Task Computing in Multi-user Fog-Radio Access Networks," in *Proceedings - International Conference on Distributed Computing Systems*, 2017, pp. 615–624.

[18] B. A. Yosuf, M. Musa, T. Elgorashi, and J. Elmirghani, "Energy Efficient Distributed Processing for IoT," *arXiv Prepr. arXiv2001.02974*, 2020.

[19] S. H. Mohamed, M. B. A. Halim, T. E. H. Elgorashi, and J. M. H. Elmirghani, "Fog-Assisted Caching Employing Solar Renewable Energy and Energy Storage Devices for Video on Demand Services," *IEEE Access*, vol. 8, pp. 115754–115766, 2020.

[20] Z. T. Al-Azez, A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Energy Efficient IoT Virtualization Framework With Peer to Peer Networking and Processing," *IEEE Access*, vol. 7, pp. 50697–50709, 2019.

[21] H. A. Alharbi, T. E. H. Elgorashi, and J. M. H. Elmirghani, "Energy efficient virtual machines placement over cloud-fog network architecture," *IEEE Access*, vol. 8, pp. 94697–94718, 2020.

[22] A. M. Al-Salim, A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Energy Efficient Big Data Networks: Impact of Volume and Variety," *IEEE Trans. Netw. Serv. Manag.*, vol. 15, no. 1, pp. 458–474, Mar. 2018.

[23] A. Al-Salim, T. El-Gorashi, A. Lawey, and J. Elmirghani, "Greening Big Data Networks: Velocity Impact," *IET Optoelectron.*, vol. 12, Nov. 2017.

[24] X. Dong, T. El-Gorashi, and J. M. H. Elmirghani, "Green IP over WDM networks with data centers," *J. Light. Technol.*, vol. 29, no. 12, pp. 1861–1880, 2011.

[25] H. M. M. Ali, T. E. H. El-Gorashi, A. Q. Lawey, and J. M. H. Elmirghani, "Future Energy Efficient Data Centers with Disaggregated Servers," *J. Light. Technol.*, vol. 35, no. 24, pp. 5361–5380, Dec. 2017.

[26] N. I. Osman, T. El-Gorashi, L. Krug, and J. M. H. Elmirghani, "Energy-efficient future high-definition TV," *J. Light. Technol.*, vol. 32, no. 13, pp. 2364–2381, Jul. 2014.

[27] A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "BitTorrent content distribution in optical networks," *J. Light. Technol.*, vol. 32, no. 21, pp. 3607–3623, Nov. 2014.

[28] A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Distributed energy efficient clouds over core networks," *J. Light. Technol.*, vol. 32, no. 7, pp. 1261–1281, Apr. 2014.

[29] J. M. H. Elmirghani *et al.*, "GreenTouch GreenMeter Core Network Energy Efficiency Improvement Measures and Optimization [Invited]," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 10, no. 2, 2018.

[30] M. O. I. Musa, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Bounds on GreenTouch GreenMeter Network Energy Efficiency," *J. Light. Technol.*, vol. 36, no. 23, pp. 5395–5405, Dec. 2018.

[31] X. Dong, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "On the energy efficiency of physical topology design for IP over WDM networks," *J. Light. Technol.*, vol. 30, no. 12, pp. 1931–1942, 2012.

[32] B. G. Bathula, B. G. Bathula, M. Alresheedi, and J. M. H. Elmirghani, "Energy Efficient Architectures for Optical Networks."

[33] B. G. Bathula and J. M. H. Elmirghani, "Energy efficient Optical Burst Switched (OBS) networks," in *2009 IEEE Globecom Workshops, Gc Workshops 2009*, 2009.

[34] T. E. H. El-Gorashi, X. Dong, and J. M. H. Elmirghani, "Green optical orthogonal frequency-division multiplexing networks," *IET Optoelectron.*, vol. 8, no. 3, pp. 137–148, 2014.

[35] X. Dong, T. El-Gorashi, and J. M. H. Elmirghani, "IP over WDM networks employing renewable energy sources," *J. Light. Technol.*, vol. 29, no. 1, pp. 3–14, 2011.

[36] X. Dong, A. Lawey, T. El-Gorashi, and J. Elmirghani, "Energy-efficient core networks," *2012 16th Int. Conf. Opt. Netw. Des. Model. ONDM 2012*, Apr. 2012.

[37] H. A. Alharbi, T. E. H. Elgorashi, and J. M. H. Elmirghani, "Impact of the Net Neutrality Repeal on Communication Networks," *IEEE Access*, pp. 1–1, Mar. 2020.

[38] L. Nonde, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Energy Efficient Virtual Network Embedding for Cloud Networks," *J. Light. Technol.*, vol. 33, no. 9, pp. 1828–1849, May 2015.

[39] H. Q. Al-Shammari, A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Service Embedding in IoT Networks," *IEEE Access*, vol. 8, pp. 2948–2962, 2020.

[40] A. N. Al-Quzweeni, A. Q. Lawey, T. E. H. Elgorashi, and J. M. H. Elmirghani, "Optimized Energy Aware 5G Network Function Virtualization," *IEEE Access*, vol. 7, pp. 44939–44958, 2019.

[41] H. Q. Al-Shammari, A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Resilient Service Embedding in IoT Networks," *IEEE Access*, vol. 8, pp. 123571–123584, 2020.

[42] M. S. Hadi, A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Patient-Centric HetNets Powered by Machine Learning and Big Data Analytics for 6G Networks," *IEEE Access*, vol. 8, pp. 85639–85655, 2020.

[43] M. Hadi, A. Lawey, T. El-Gorashi, and J. Elmirghani, "Using Machine Learning and Big Data Analytics to Prioritize Outpatients in HetNets," in *INFOCOM 2019 - IEEE Conference on Computer Communications Workshops, INFOCOM WKSHPS 2019*, 2019, pp. 726–731.

[44] M. S. Hadi, A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Patient-Centric Cellular Networks Optimization Using Big Data Analytics," *IEEE Access*, vol. 7, pp. 49279–49296, 2019.

[45] I. S. B. M. Isa, T. E. H. El-Gorashi, M. O. I. Musa, and J. M. H. Elmirghani, "Energy Efficient Fog-Based Healthcare Monitoring Infrastructure," *IEEE Access*, vol. 8, pp. 197828–197852, 2020.

[46] M. Musa, T. Elgorashi, and J. Elmirghani, "Bounds for energy-efficient survivable IP over WDMnetworks with network coding," *J. Opt. Commun. Netw.*, vol. 10, no. 5, pp. 471–481, May 2018.

[47] M. Musa, T. Elgorashi, and J. Elmirghani, "Energy efficient survivable IP-Over-WDM networks with network coding," *J. Opt. Commun. Netw.*, vol. 9, no. 3, pp. 207–217, Mar. 2017.

[48] C. Gray, R. Ayre, K. Hinton, and R. S. Tucker, "Power consumption of IoT access network technologies," in *2015 IEEE International Conference on Communication Workshop, ICCW 2015*, 2015, pp. 2818–2823.

[49] A. Hammadi, M. Musa, T. E. H. 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*, 2016, pp. 178–182.

[50] S. P. E. Corporation, "SPECpower_ssj2008," 2017. [Online]. Available: https://www.spec.org/power_ssj2008/results/res2017q3/power_ssj2008-20170829-00780.html. [Accessed: 12-Mar-2021].

[51] Cisco, "Cisco ME 4600 Series Optical Network Terminal Data Sheet - Cisco," 2013. [Online]. Available: https://www.cisco.com/c/en/us/products/collateral/switches/me-4600-series-multiservice-optical-access-platform/datasheet-c78-730446.html. [Accessed: 12-Mar-2021].

[52] K. Grobe, M. Roppelt, A. Autenrieth, J. P. Elbers, and M. Eiselt, "Cost and energy consumption analysis of advanced WDM-PONs," *IEEE Commun. Mag.*, vol. 49, no. 2, Feb. 2011.

[53] J. M. H. Elmirghani *et al.*, "GreenTouch GreenMeter core network energy-efficiency improvement measures and optimization," *J. Opt. Commun. Netw.*, vol. 10, no. 2, pp. A250–A269, Feb. 2018.