Energy Consumption of Hybrid Data Center Networks

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***Abstract*—Existing data center networks (DCNs) based on only electronic packet or all-optical switching still pose an exponential increase in power consumption and cost due to the current high demand for digital data and sustainability issues. The recent development of hybrid DCN prototypes is a promising solution offering relatively higher data throughput, low latency, reduction in cost and energy consumption. This paper explores the frontier of hybrid DCN with a special focus on energy consumption and cost. We evaluate the energy consumption per bit and the greenhouse gas (GHG) emission per year of three hybrid switching systems as compared with an optical point to point (ptp) network, results show that the hybrid switching systems will consume less energy per bit and are likely to emit less GHG annually. We present feasibility analysis on the energy consumption and cost of some hybrid DCN prototypes. Evaluation results show that Helios-like and Hybrid Optical Switching-like prototypes achieve a power usage effectiveness (PUE) value lower than 1.2, an index which represents a very efficient level of energy performance in a data center network.**

***Index Terms*—Data center networks, Hybrid switching systems, Energy consumption, Network performance analysis.**

I. Introduction

DATA centers currently support and enable service economies in the way heavy industries supported manufacturing during the 1920s. Data center networks (DCNs) have been phenomenal in communication systems over the past decades, but their drawbacks such as high power consumption, high cost and unsustainable network traffic should not be overlooked. A very large data center network may consume 30 gigawatt per hour (GWh) of power in a year. Large-scale data centers need massive infrastructure of cooling systems. As a data center grows, it becomes harder to focus on a target area for cooling since the walls of data centers act as heat sinks, increasing the cost of cooling per square foot [1]. The power load for a data center network is further discussed and presented by researchers in [2]. Energy is usually the largest single element for the capital expenditures (CAPEX) and operating expenses (OPEX) in data center networks, the indirect impact of energy consumption in the world today cannot be overemphasized.

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Hybrid data center network (HDCN) offers a possible solution to the current state of high demand and rapid growth in network traffic, along with the exponential increase in power consumption and cost of DCNs by integrating multiple switching schemes to make use of their numerous advantages. A typical hybrid DCN constitutes a multiplicity of switching schemes such as the optical packet switching (OPS), optical burst switching (OBS), optical circuit switching (OCS) and electronic packet switching (EPS) [3], [4]. This integration of schemes or switching systems allows for a new and enabling technology capable of transforming current data center networks to an agile and flexible kind. Resource allocation is employed in hybrid DCN to enable optimal data flow within each switching scheme in order to improve the energy efficiency level of the entire network and to satisfy performance requirement conditions [5]. Efficient scheduling in hybrid switching systems impacts significantly on the entire network. Some examples of scheduling algorithms for hybrid switching systems are given in [6]–[9].

Majority of work done on hybrid DCN energy consumption mainly focuses on optical interconnect categorization and their spectral efficiency. Researchers in [6] showed that the construction of hybrid DCN is the most cost and energy-efficient way for DCN upgrading while offering high quality of service. They evaluated the benefits brought by the flexibility of OPS/OCS hybrid scheme. Further work is done by [10]. They explored the feasibility and applicability of optical switching in hybrid data center networks, focusing mainly on the Helios and c-Through prototypes.

The contribution of our work is twofold. First, we conduct simulation on the energy consumption of different hybrid DCN architectures. We then place our analysis in a more realistic context, in which well-known prototypes of hybrid DCNs are studied, and their applicability under different network requirements are compared in a tabular form. We evaluate and present numerical analysis on the power consumption, cost and CO_2 emission of these hybrid DCN prototypes.

The rest of this paper is organized as follows: In Section II we consider the energy consumption of hybrid switching systems and present numerical evaluation of their comparative functions.

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In Section III we evaluate the power consumption and cost of some well-known hybrid DCN prototypes and their potential environmental impact. We finally discuss pending challenges that may affect the sustainability of hybrid data center networks. Section IV concludes the paper.

II. Energy consumption of hybrid switching systems and Application scenarios

Hybrid solutions which combine circuit and packet switching in the optical domain yield low power consumption and high performance [5], [6], [11], [12]. We evaluate the energy per bit and the greenhouse gas (GHG) emission per year of three hybrid switching systems as compared with an optical point to point (ptp) network. Method used for the GHG emission conversion can be found in [13]. In our evaluation we exclude the power consumption of the support infrastructure equipment. Since the data traffic flow that remains within large-scale data centers currently account for over 40% of total traffic within all data centers and will account for 55% by 2021 [14], we therefore simulate only the traffic that remains within the data center, focusing primarily on the network equipments (NE) (i.e. ToR switches, aggregation switches and core switches). The power consumption for the different switching schemes in each hybrid DCN can be given as:

$$P_{\text{NE}}^{\text{Scheme}} = N_T \cdot N \cdot P_{\text{ToR}} + N \cdot P_{\text{Agg}}^{\text{Scheme}} + P_{\text{Core}}^{\text{Scheme}} \qquad (1)$$

Here, P denotes power consumption, *Scheme* indicates the type of hybrid switching system (i.e. either OCS OPS OBS EPS, OCS EPS or OPS EPS), N_T is the number of ToR nodes and N is the number of aggregation nodes. The power consumption of the optical ptp network is given as follows:

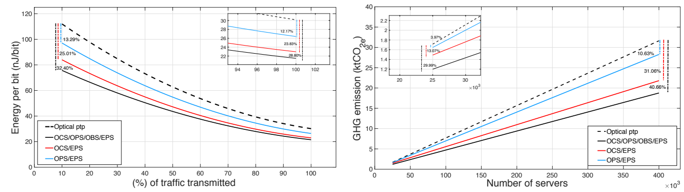
$$P_{\text{NE}} = N_T \cdot N \cdot P_{\text{ToR}} + N \cdot P_{\text{Agg}} + P_{\text{Core}} \qquad (2)$$

The configurations used for simulation is shown in Table I. We assume all switching fabrics of the three hybrid systems have the same number of active components during simulation.

TABLE I
SIMULATION PARAMETERS

Configuration	Value
Servers per rack	48
ToR Switches	64
Aggregation Switches	32
Total Amount of Servers	96,000
Wavelength per fiber	64
Cabling at ToR & Agg	40Gbps
Traffic distribution	Lognormal

Fig. 1(a) shows the energy consumption per bit of traffic transmitted successfully by different hybrid switching schemes in comparison with that of the optical ptp network. The hybrid switching scheme of (OCS OPS OBS EPS) has the most energy savings ranging between 28.80% and 32.40%. Our evaluation included ToR and aggregation switches for each of the switching systems mentioned, a detailed explanation of the model used for the estimation of power consumption and configuration of the optical ptp network can be found in [15].



(a) (b)

Fig. 1: Comparison of hybrid switching schemes to optical ptp networks. (a) Energy consumption per bit of flow transmitted successfully for different hybrid switching schemes as compared with optical ptp network. (b) Greenhouse gas emission per year of hybrid switching systems relative to optical ptp networks.

Fig. 1(b) shows the GHG emissions per year for different hybrid switching schemes as compared with optical ptp network. There is an exponential increase in GHG emission as the number of servers in the data center grows. When the number of servers increase from 25K to 400K, the reduction in GHG emissions offered by the hybrid switching scheme of OCS/EPS increases from 13.07% to 31.06%. The GHG emissions are expressed in metric kilotons (kt) of carbon dioxide equivalent (CO_{2e}) generated by DCNs per year.

The blocking loss curve (BLOC) defined in [5] shows that the more resource allocated to an optical switch in a hybrid switching system the lower energy is consumed in the entire network. However, there is a trade-off when considering the high cost of optical switches, optical transceivers and other optical components. Finding the balance between cost, energy consumption and resource allocation is vital in hybrid switching systems. We therefore discuss qualitative comparisons and present suitable ways of adopting hybrid switching schemes. Table II shows some application scenarios for the implementation of hybrid switching in data center networks.

1) OCS and EPS: The combined switching scheme of OCS and EPS employs relatively low level of inter-ToR network capacity distribution and efficiently manages long-lived bulk data transfer which results in a relatively moderate complexity, high capacity and low cost [6], [16].

2) OPS, OBS, OCS and EPS: This scheme enables adequate mapping of each application to a given transport mechanism that best satisfies its inherent traffic demands, thus, allowing for instant service differentiation in the optical layer. Before a burst deployment in an OBS, a control packet is generated and forwarded towards the output port to establish a one-way resource reservation resulting in high flexibility [17]. Meanwhile, the offset-time sent prior to burst deployment also ensures reduced loss probability and enables the implementation of different service classes. Since three of these four switching schemes are optically transmitted via a wavelength division multiplexing (WDM) collectively, they are able to provide higher data rates over long transmission channels than the electrical transmission systems, thus, resulting in lower power consumption [15].

3) OPS and EPS: The OPS in this scheme offloads traffic from the EPS core which enables the data center to grow by approximately 25x without increasing capacity of the existing EPS core. This is achieved by issuing packet compression in the

TABLE II
APPLICATION SCENARIOS OF HYBRID SWITCHING SCHEMES

Switching Scheme	**Performance**				**Energy consumption**	**Cost**
	Scalability	Complexity	Capacity	Flexibility		
OCS EPS	Moderate	Moderate	High	Low	Moderate	Low
OPS OBS OCS EPS	High	High	Moderate	High	Low	Moderate
OPS EPS	High	High	High	Low	High	Moderate

network to increase the inter-frame gap. Employing OPS and EPS switching scheme to the core network of the intra-data center platform ensures a relatively high bandwidth capacity and high switching speed [18].

III. Energy Efficiency in Hybrid DCN Prototypes

In this section we present an empirical study on the relationship of energy consumption and cost of some hybrid data center network prototypes and their future prospects.

A. *Energy Consumption and Cost*

In an attempt to confront the drawbacks of traditional data center networks (DCNs) such as the increase in power consumption and cost, low data throughput and latency, hybrid DCN prototypes have been proposed by various research groups with a couple of notable mentions in Table III.

Several metrics exist for the assessment of energy consumption in DCNs, we adopt the power usage effectiveness (PUE) metric proposed by [19] in this paper. PUE illustrates how efficiently data centers utilize their power resources. It is determined by the ratio of *Total Facility Power* of a given data center network to *IT Equipment Power*. The overall efficiency of the data center improves as the PUE quotient decreases toward 1 (i.e., maximum attainable efficiency without overhead energy consumption). PUE measurements helps data center administrators and organizations benchmark their overall operations and to identify opportunities to increase efficiency.

Although the PUE trend of data center networks has seen a good decline since 2009 [20], it still remains relatively high in comparison with the ideal PUE value of 1.0 [19]. The performance level of energy consumption in current data center networks is between average and efficient index, hence the need for much improvement. When PUE index improves the energy consumption in a data center network reduces. Thus, we conduct an estimation of cost and CO_2 emission reduction from PUE improvement respectively. The annual cost to run data center severs can be defined as server power cost (SPC) [21], and calculated as follows:

$$\text{SPC} = \frac{Average\ Power\ (W)}{1000} * 8760 \left(\frac{hours}{year}\right) * PUE * \frac{Cost}{kWh} \tag{3}$$

The improvement of energy performance in a data center network can be represented by ΔPUE. We use the average PUE of current data center networks (1.61) as a reference value [20]. We therefore represent the improved PUE value of a DCN as k, where k is $\in$ [1, 1.61]. Hence:

$$\Delta\text{PUE} = \mid k - 1.61 \mid, \;\; k \in [1, 1.61], \;\; \Delta PUE \in [0, 0.61] \tag{4}$$

For further analysis we consider a data center consisting of 1024 servers, the saving cost (SC) caused by the reduction of power consumption can be calculated as follows:

$$\text{SC} = 1024 * \frac{Average\ Power\ (W)}{1000} * 8760 \left(\frac{hours}{year}\right) * \Delta PUE * \frac{Cost}{kWh} \tag{5}$$

Based on the trending relationship between saving cost, reduction in CO_2 emission and ΔPUE (improved power usage effectiveness), we can further analyze the economical and ecological impact of the energy performance and CO_{2e} of hybrid data center networks in a more qualitative and comprehensive manner as shown in Fig. 2(a). The figure shows a trend in cost saving and CO_2 emission reduction when ΔPUE increases. The relationship between power usage effectiveness (PUE) and CO_2 emission factor is discussed in [13], [22].

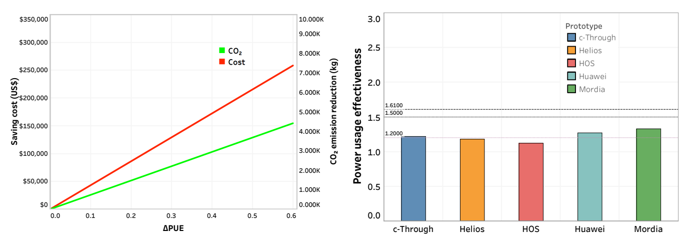


Fig. 2: (a) Relationship of DCN cost savings and CO_2 emission reduction to ΔPUE. The trend shows cost saving and CO_2 emission reduction when ΔPUE increases. (b) Estimated Power Usage Effectiveness of five hybrid DCN prototypes.

We further calculate the estimated PUE of these hybrid DCN prototypes: Helios, c-Through, HOS, Huawei hybrid DCN and Mordia. Here we define the total facility power of a hybrid DCN as the sum of energy consumed by IT equipments and by support infrastructure equipments. We assume that the energy consumed by IT equipments is mainly from servers and network components (i.e. ToR switches, aggregation switches and core switches). Energy consumed by support infrastructure equipments is mainly from cooling system, lightening and power supply chain. The parameters and configuration used to evaluate the prototypes are shown in Table I and III.

Fig. 2(b) shows that PUE of the five hybrid DCN prototypes is relatively lower than 1.61, which has been the average PUE value of data center networks in recent years [20]. Moreover, among these five prototypes, Helios and HOS architecture

TABLE III
HYBRID DCN PROTOTYPE COMPARISON

Prototype	Switching Technology				Topology	Components	Power [W]	Estimated Cost [US$]
	OCS	OPS	OBS	EPS				
Helios [23]	✓			✓	2-Tier	Glimmerglass (MEMS based OCS switch) $_{core}$	0.24 W	NA
						Fulcrum Monaco 24-port 10 GigE packet switch $_{core}$	12.5 W	US$707.00
						MEMS switch $_{core}$	0.1 W	US$36.00
						XFP DWDM transceivers (wavelengths = 32) $_{agg}$	3.5 W	US$427.00
						Dell 48-port GigE packet switch $_{pod}$	12.5 W	US$650.00
c-Through [16]	✓			✓	3-Tier Spanning Tree	10 Gbit Optical transceivers $_{core}$	3.5 W	US$300.00
						10 GigE 48 port $_{core}$	12.5 W	US$898.00
						MEMS switch $_{core}$	0.1 W	US$36.00
						WDM $_{agg}$	2.5 W	US$369.00
						Socket Buffers $_{ToR}$	NA	NA
HOS [15]	✓	✓	✓	✓	3-Tier	Electronic CMOS switch $_{core}$	8 W	US$114.00
						Line card $_{core}$	300 W	US$534.00
						SOA switch $_{core}$	20 W	US$1290.00
						Optical Amplifiers $_{core}$	14 W	US$1190.00
						Control info extraction/reinsertion $_{core}$	17 W	NA
						MEMS switch $_{core}$	0.1 W	US$36.00
						Resource allocator $_{edge}$	296 W	NA
						Tunable wavelength converter $_{edge}$	1.69 W	NA
						Classifier $_{edge}$	62 W	NA
						Assembler $_{edge}$	62 W	NA
						Packet extractor $_{edge}$	25 W	NA
Huawei [18]		✓		✓	3-Tier	4×4 PLZT photonic switch $_{core}$	18 W	NA
						10 GigE Arista 7148 SW $_{core}$	12.5 W	US$898.00
						1310 nm SFP+ transmitter $_{agg}$	0.85 W	US$20.00
						1550 nm XFP convertor $_{agg}$	3.5W	US$380.00
Mordia [24]	✓			✓	Unidirectional Ring	Nistica 100 WSS (TI DLP binary MEMS based) $_{core}$	NA	NA
						Optical Amplifiers $_{core}$	14 W	US$1190.00
						Variable Optical Attenuators $_{core}$	0.3 W	US$246.00
						DWDM SFP+ $_{core}$	1.85 W	US$369.00
						10 GigE $_{agg}$	12.5 W	US$898.00

achieves a PUE value lower than 1.2, an index which indicates a very efficient level of energy performance in a DCN [19].

B. Challenges

The development of hybrid data center networks (DCNs) faces economical and ecological challenges. The cost of components in data center networks is inextricably linked to energy consumption and performance. Hybrid data centers often require long links for network interconnection, and hence optical transceivers have become a necessity [23]. However, the high cost of optical transceivers is a challenging issue for modern data centers limiting their scalability and performance. Although hybrid data center networks serve as a better option to traditional data center networks, cooling system, lightening and power supply chain still take up an estimated 45% of the total facility power, giving a high propensity of cost incurrence and consequential greenhouse gas (GHG) effect depending on the network size. The relationship between cost and CO_{2e} cannot be overemphasized, the financial implications and environmental effects are significant. Sustainability has become a real challenge in this aura of technological modernity. Companies need to be publicly committed to science-based targets (SBTs) on greenhouse gas reduction.

IV. Conclusions and Future Work

In this paper, we present an overview of some hybrid DCN switching schemes, prototypes and related energy consumption. We evaluate the energy per bit and the greenhouse gas (GHG) emission of three hybrid switching systems as compared with an optical point to point (ptp) network. We then outline application scenarios best suitable for these hybrid switching schemes. One of the most significant concern behind the numerous proposals of hybrid DCN lies in the constant increase in energy consumption and its associated greenhouse gas emissions effect and cost. We therefore analyze the potential power usage effectiveness, greenhouse gas emission effect and relative cost of five hybrid DCN prototypes. Finally, we highlight some pending economical and ecological challenges. Our future work will focus on the optimization of hybrid switching systems by employing the best practices of traffic partitioning in order to find the fine line between cost, energy consumption and resource allocation against the ever rising demand and sustainability of data traffic in large-scale DCNs.

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References

[1] Kevin Normandeau. Two-Phase Modular Cooling for the Data Center. http://www.datacenterknowledge.com/archives/2010/05/24/two-phase-modular-cooling-for-the-data-center/, May 2010.

[2] Ebrahimi, Khosrow, Gerard F. Jones, and Amy S. Fleischer. A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renewable and Sustainable Energy Reviews 31 (2014): 622-638.

[3] C. M. Gauger, et al., Hybrid Optical Network Architectures: Bringing Packets and Circuits Together, IEEE Communications Magazine, August 2006.

[4] Chun Tung Chou, Farzad Safaei, Paul Boustead, Iradj Ouveysi: A hybrid optical network architecture consisting of optical cross connects and optical burst switches. ICCCN: 53-58 2003.

[5] Feng, Zhangxiao, et al. Resource allocation in electrical/optical hybrid switching data center networks. IEEE/OSA Journal of Optical Communications and Networking 9.8 (2017): 648-657.

[6] Shu, Yi, et al. Programmable OPS/OCS hybrid data centre network. Optical Fiber Technology 44 (2018): 102-114.

[7] Tseng, Shih-Hao, Bo Bait, and John CS Lui. Hybrid Circuit/Packet Network Scheduling with Multiple Composite Paths. IEEE INFOCOM 2018-IEEE Conference on Computer Communications. IEEE, 2018.

[8] Nathan Farrington, George Porter, Yeshaiahu Fainman, George Papen, Amin Vahdat: Hunting mice with microsecond circuit switches. HotNets 2012: 115-120.

[9] Imran, Muhammad, et al. HOSA: Hybrid optical switch architecture for data center networks. Proceedings of the 12th ACM International Conference on Computing Frontiers. ACM, 2015.

[10] Hamid Hajabdolali Bazzaz, et al. Switching the optical divide: Fundamental challenges for hybrid electrical/optical datacenter networks. Proceedings of the 2nd ACM Symposium on Cloud Computing. ACM, 2011.

[11] Aleksi, Slavia. Electrical power consumption of large electronic and optical switching fabrics. Photonics Society Winter Topicals Meeting Series (WTM). IEEE, 2010.

[12] Divakaran, Dinil Mon, Soumya Hegde, Raksha Srinivas, and Mohan Gurusamy. Dynamic resource allocation in hybrid optical electrical datacenter networks. Computer Communications 69 (2015): 40-49.

[13] Uddin et al., Energy efficiency and low carbon enabler green IT framework for data centers considering green metrics. Renewable and Sustainable Energy Reviews 4078-4094: 16.6 (2012).

[14] Networking, Cisco Visual. Cisco global cloud index: Forecast and methodology, 20162021. White paper. Cisco Public, San Jose (2016).

[15] Matteo Fiorani, Slavisa Aleksic, Maurizio Casoni: Hybrid Optical Switching for Data Center Networks. J. Electrical and Computer Engineering 2014:139213:1-139213:1 2014.

[16] G. Wang, D. G. Andersen, M. Kaminsky, K. Papagiannaki, T. E. Ng, M. Kozuch, M. Ryan, c-through: part-time optics in data centers, SIGCOMM Comput. Commun. Rev. 41 (4) 2010.

[17] Aracil, Javier, and Franco Callegati, eds. Enabling optical internet with advanced network technologies. Springer Science & Business Media, 2009.

[18] Bernier, Eric, et al. A hybrid photonic-electronic switching architecture for next generation datacenters. Silicon Photonics X. Vol. 9367. International Society for Optics and Photonics, 2015.

[19] Grid, Green. The Green Grid data center power efficiency metrics: PUE and DCiE.Green Grid report (2007).

[20] Avgerinou, Maria, Paolo Bertoldi, and Luca Castellazzi. Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency.Energies10.10 (2017): 1470.

[21] Cole, David. Data center energy efficiency looking beyond PUE. No Limits Software, White Paper4 (2011).

[22] Joe Kozlowicz. The Truth About Data Center Carbon Emissions and PUE. Green House Data, Wednesday, May 7th (2014).

[23] Farrington, Nathan, et al. Helios: a hybrid electrical/optical switch architecture for modular data centers. ACM SIGCOMM Computer Communication Review 41.4 (2011): 339-350.

[24] Farrington, Nathan, et al., A 10 us hybrid optical-circuit/electrical-packet network for datacenters. Optical Fiber Communication Conference. Optical Society of America, 2013.