Evolution of Data Centers: A Critical Analysis of Standards and Challenges for FSO Links

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***Abstract*—As the bandwidth-intensive and performance-sensitive application portfolio broadens, so does the interest in *data center networks (DCNs)* by network research community. Most DCNs deployed today are wired DCNs in which copper and optical fiber cables are used for communication. Despite recent advances in DCN design, there are two inevitable problems facing wired DCNs; *hotspots* and *cabling complexity*. To alleviate these problems, recent research works explore the integration of wireless technologies, such as, free space optical (FSO) communication or 60 GHz radio frequency, into DCNs. Wireless links can be used to augment conventional wired DCNs, or to realize a pure wireless DCN. In this paper, we discuss and analyze challenges that may face FSO-DC designers, and identify standardization needs and opportunities to help accelerate the development of FSO links for DCNs. To this end, we review state of the art of wireless DCNs using FSO links. We also briefly review and summarize physical layer specifications of existing standards related to indoor FSO communication, such as, IEEE 802.11 standard, IEEE 802.15.7 standard for visible light communications (VLC), and the families of standards developed by the Infrared Data Association (IrDA) and the VLC Association (VLCA).**

I. INTRODUCTION

Data Center (DC) design paradigm has been evolving to facilitate the development of mega DCs that support 100,000 servers and beyond [1]. The demand for mega DCs has been increasing as the portfolio of bandwidth and computation intensive Big Data applications continues to grow [2]. Examples of Big Data applications can be found in disciplines like social media, bioinformatics, Internet-of-Things (IoT), nanoinformatics, and real-time research analytic services.

A *DC network (DCN)* is the DC networking infrastructure that provides all intra- and inter-DC networking services. It is, therefore, essential to design efficient high-speed/high-bandwidth DCNs to maximize the total aggregated computing and communication capacities in mega DCs [3]. Thus, academia and industry are continuously developing and integrating new technologies into the design of DCNs, and we are witnessing an evolution in the design space of DCNs [2].

Analysis of real world DC traffic statistics shows that some applications do have unpredictable traffic patterns and unbalanced traffic distributions that can lead to temporary *hotspots* [4]. It is difficult for conventional tree-based DCN architectures to adapt to the unpredictable changes in traffic patterns. Current trends in high-speed/high-bandwidth DC applications show that the hotspot problem is likely to worsen in the future [5]–[7]. In order to accommodate the worst case scenario, an over-deployment of cables is needed leading to *cabling complexity* problems (e.g., cable management, maintenance, and heat dissipation) [3], [8]. Available DC designs offer little or no cost-performance tradeoffs. For example, the low-cost designs sacrifice performance. On the other hand, only over-provisioned high-cost designs offer reasonable performance.

A different approach to tackle the hotspot problem is to establish on-demand links between nodes that are likely to develop a hotspot [4]. The on-demand links can be based on a wired or a wireless technology. At the scale of mega DCNs, realizing on-demand wired links require larger number of cables escalating problems related to cabling complexity. On the other hand, the potential capability of establishing flexible on-demand wireless links have motivated the researchers to investigate wireless communication as a possible solution for hotspot and cabling complexity problems, simultaneously. There are two candidate wireless technologies, radio frequency (RF) and free space optics (FSO), also known as optical wireless communication (OWC) [2]. For the sake of brevity, we use the terms FSO, and OWC interchangeably in this paper.

Ramachandran et al. propagated the idea of using 60 GHz RF technology in DCN design [13]. Following their work, considerable research has been devoted to investigating the feasibility of deploying 60 GHz RF technology in DCNs [7], [8], [14]–[16]. Although 60 GHz can offer high data rates, since high carrier frequencies are used, 60 GHz technology has its limitations as it has lower practical bandwidth, and suffers from high attenuation and propagation loss [10], [11], [13]. Moreover, RF propagation at high carrier frequencies becomes more line-of-sight (LOS) dependent and the key features of RF technologies, such as, mobility, coverage, and receiver sensitivity, become unclear [17]. Radiation patterns of RF impose additional restrictions on the activity of wireless modules in close proximity because of interference [18]. This can increase the complexity of routing and network management, and reduces the throughput [7].

The advantages of FSO technology and its success in a wide range of applications has motivated researchers to investigate the use of FSO in the design of DCNs [2], [10]–[12]. Examples of applications in which FSO has already found its place are, mobile networks backhaul, space communication, and underwater sensing. Moreover, FSO is now seen as a complement

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TABLE I: Summary of Major FSO DC Research.

DC Type	Highlights	Reference	Year
Hybrid	Suggest the use of mechanical pedestals to establish LOS inter-rack FSO links.	Riza et al. [9]	2012
Hybrid	FireFly, a flexible wireless DC using FSO for inter-rack communication. Prototype and simulations are presented.	Hamedazimi et al. [10], [11]	2013, and 2014
Pure	FSO-Bus to connect multiple adjacent network components using point-to-point FSO links. Design of a switch-free FSO rack and FSO-DC.	Hamza et al. [2]	2014
Pure	Racks arranged in circular cells, where ToRs in neighboring racks communicate using LOS FSO links. They also communicate with aggregate (or core) switches located at a physically higher layer	Arnon [12]	2015

technology for RF in next-generation communication systems, such as 5G wireless networks [19]. The notable spread of FSO technology in different applications is due to the advantages presented by FSO technology, such as, high data rate, lower interference as compared to RF [17], and high speed of light that is approximately 1.5 times faster than that of fiber optics, which means less latency [2].

Few indoor FSO standards have been developed, including the personal area network standards developed by the Infrared Data Association (IrDA) and IEEE 802.15.7 for visible light communication (VLC). None of the available standards, however, is compatible with FSO links for DCNs. Therefore, it is important to understand the requirements imposed by DCs on FSO links to identify potential standardization needs to help accelerate the development of FSO links for DCs.

The remainder of this paper is organized as follows. We dedicate Section II to review the state of the art of FSO-DCs. In Section III, we briefly review existing standards related to indoor FSO communication. We investigate challenges that may face standardization organizations during the process of standardizing FSO links for DCs in Section IV. Finally, a summary is given in Section V.

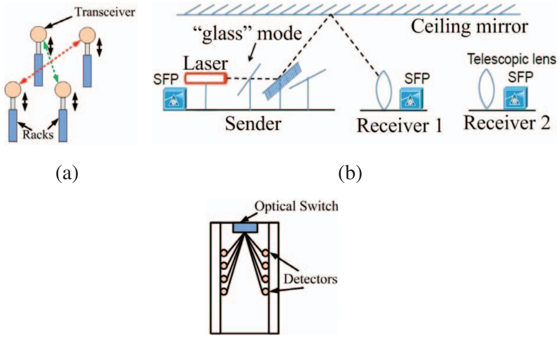
II. FSO-DCs: State of the Art

Motivated by the advantages and recent advances in FSO technology, researchers started to consider the deployment of FSO in DCs. In [20], [21], Chowdhury et. al. experimentally demonstrate transmission of 10 Gbps cable television (CATV) radio frequency signals over a point-to-point indoor FSO link. Results show that the 15 m FSO link established is almost lossless. Good alignment of the transmitter and receiver collimators is crucial to receive sufficient optical power.

FSO can be used to augment existing wired DC infrastructure by adding inter-rack wireless links leading to a hybrid DCN, or to completely replace the wired infrastructure with a pure wireless network. Hybrid DCs may solve the problem of hotspots and alleviate the wiring complexity problem. On the other hand, pure wireless DC is expected to solve the hotspot and wiring complexity problems.

Only few papers [2], [9]–[12], [22]–[24] and patents [25]–[27] discuss the incorporation of FSO in DCs. Table I summarizes major FSO-DCs research.

In [9], Riza et al. suggest realizing inter-rack FSO links inside DCs using pedestal platform on top of rack (ToR). The arm holding a transceiver and connected to the pedestal allows vertical and rotational movement such that LOS links are established between different racks [see Figure 1-(a)].



(a) (b)

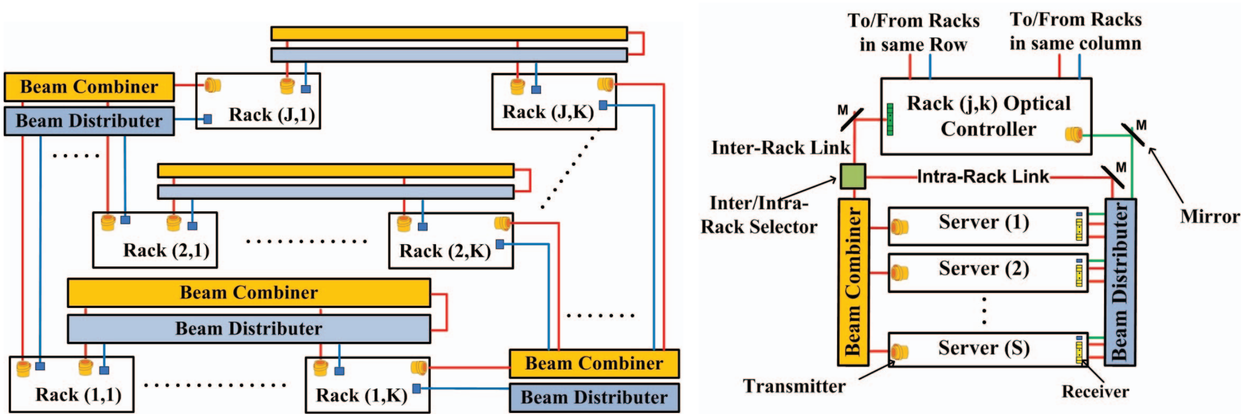
(c)

Fig. 1: Proposed design by (a) Riza et al. [9]. (b) Hamedazimi et al. [10]. (c) Joseph et al. [26]

Hamedazimi et al. propose *FireFly*, a DCN in which FSO links are used for inter-rack communication [10], [11]. Similar to the 60 GHz *Flyways* [15], all inter-rack communications in FireFly are performed using links that are reflected off of a reflector (mirror) mounted to the ceil. As shown in Figure 1-(b), steerable FSO transceivers are placed on ToR. In order to perform link steering, the authors propose the use of switchable mirrors (SMs) or Galvo Mirrors (GMs). In the case of SMs, every FSO transceiver is equipped with several SMs. The SMs are pre-configured and aligned to a receiving FSO on a different rack. According to the states of SMs (i.e., glass or mirror), a link is directed to devices on other racks through the reflection off of a mirror mounted to the ceil. Links are established by switching relevant SMs to mirror and transparent states. On the other hand, a GM is a small mirror mounted on an axis that has limited rotation capability. A link is established by proper rotation of the mirror that deflects the incident laser beam. The positioning error is found to be $\leq 10\ \mu$rad (i.e., 1 mm at a distance of 100 m). This error is, thus, within the commonly accepted threshold in FSO links of 6 mm at 100 m.

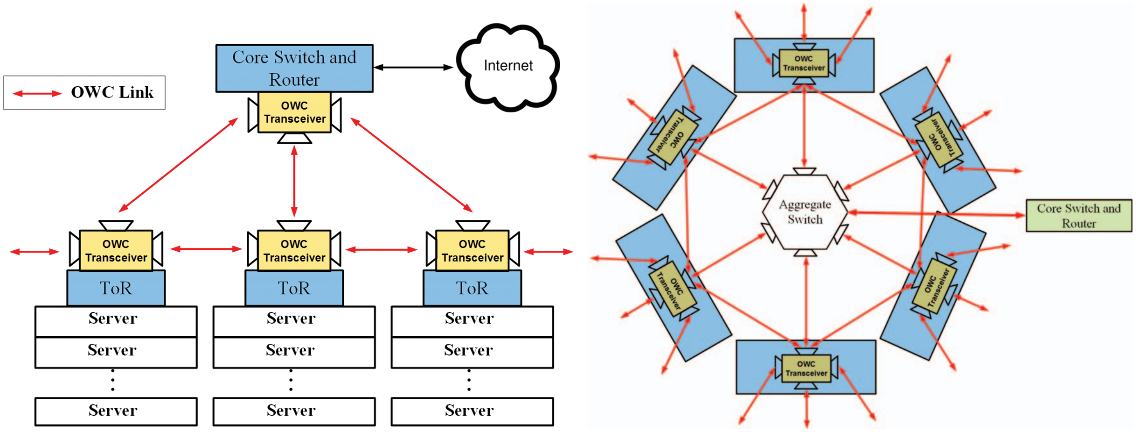
In [25], Kuo et al. propose the connection of the servers in the rack using FSO. However, the connection is limited to the adjacent servers. Therefore, a rack that contains large number of servers will have a limited intra-rack connectivity.

A patented bi-directional point-to-point FSO link design is envisioned to be used for intra- and inter-rack communication inside DCs [26]. For intra-rack communication, Joseph et al. suggest using a ToR optical switch employing a multiple-lens array. Servers in the rack send information to the ToR



(a) (b)

Fig. 2: Our proposed design in [2]. (a)FSO-DC. (b) Fully connected FSO rack.



(a) (b)

Fig. 3: Proposed design by Arnon in [12] (a) Side view. (b) Top view.

Switch [see Figure 1-(c)]. The optical switch then directs the information back to the servers using data shower beams. In this design, the optical switch must be equipped with number of transceivers equal to the number of servers to establish point-to-point FSO links. Moreover, as the number of servers increase, the width of the rack must increase to maintain the LOS with the servers near the bottom of the rack.

In another patent [27], Davidson et. al. present an extensive theoretical discussion of a DC using FSO. Davidson et. al. discuss connecting DC components such as: servers, racks or a set of racks using FSO, mirrors, beam splitters, and switches to realize the FSO links, however, the inventors do not discuss the means of connecting multiple components using FSO.

A common impediment for most FSO-DC designs is the difficulty of connecting multiple adjacent components using FSO. This is because LOS links can not be easily maintained as other components get in between the source and destination need to be connected leading to risk of link blocking [2].

In a typical DC [see Figure 2-(a)], racks are deployed in a row-based arrangement with $\mathcal{J}$ rows, each contains $\mathcal{K}$ racks. A rack can be uniquely identified by a tuple (j, k), (where $1 \leq j \leq \mathcal{J}\ and\ 1 \leq k \leq \mathcal{K}$). Each rack contains $\mathcal{S}$ servers.

To achieve high data rate between servers in a rack, servers must be connected using point-to-point FSO links. However, since servers are stacked on top of each other, it is very difficult to maintain a LOS point-to-point links. Therefore, we propose *FSO-Bus* that can be used to connect any array of adjacent components using point-to-point FSO links [2].

Fig. 2-(b) shows an FSO rack using FSO-Bus. In our design, each server is equipped with an optical transmitter on one side of the server, and an optical receiver comprising one or an array of photodetectors on the opposite side. The main idea is to direct the transmitted beams either for intra-rack, inter-rack, or both communications, using the intra/inter-rack selector (which is a 1×2 FSO switch). For intra-rack communication, a beam is directed to the other side of the rack where receivers are placed. Using a beam distributer, beam is distributed to all servers allowing *switch-free* intra-rack communication. For inter-rack communication, the combined beam is directed to the *Rack Optical Controller (ROC)*. ROCs in the same row/column of racks can be connected using the FSO-Bus.

In case of intra-rack communication, S light beams from the S servers can be transmitted and received by all servers, simultaneously, using beam splitters (BSs) placed in front of the server to be able to intercept the beams. Each transmitter

TABLE II: Summary of Existing Indoor FSO Standards

Attribute	**IEEE 802.11**	**IrDA**						**IEEE 802.15.7**		
		SIR	**MIR**	**FIR**	**VFIR**	**UFIR**	**Giga-IR**	**PHY I**	**PHY II**	**PHY III**
Environment	Indoor	Indoor						Outdoor	Indoor/ Outdoor	Indoor
Coverage Type	Cellular	point-to-point						Cellular		
LOS	NLOS	LOS						LOS		
Mobility	Mobile	Fixed						Mobile		
Link Distance (Range)	$\leq$ 10 m	60 cm - 1 m					6 cm	$\leq$ 10 m		
Wavelength	850-950 nm	850-900 nm						380-780 nm		
Data Rate	1 and 2 Mbps	2.4-115.2 kbps	0.576 and 1.152 Mbps	4 Mbps	16 Mbps	96 Mbps	0.512 and 1.024 Gbps	11.6 to 266.6 kbps	1.25 to 96 Mbps	12 to 96 Mbps
Status	Suspended	Active						Active		

has a separate optical path connecting it to all other servers. Therefore, there are no collision domains, instead, each server has its broadcast domain which must be managed efficiently so that data are delivered to the intended destination(s) only. Many networking and addressing schemes can be used, such as, Time Division Multiple Access (TDMA), or Wavelength Division Multiplexing (WDM).

For inter-rack communication, an ROC receives data from other racks to deliver to server(s) in the rack or to relay it to other racks in its subnetwork. An ROC is expected to handle large amount of traffic, and thus we envision the use of wavelength division multiplexing (WDM) or dense WDM (DWDM) to increase inter-rack link capacities.

In [12], Arnon discusses both, intra-rack and inter-rack communications using FSO. For intra-rack communication, an envision similar to our FSO-Bus is proposed where servers communicate with each other and with the ToR using inter-server OWC transceivers. However, the structure and the means of establishing FSO links using inter-server OWC transceivers are not discussed.

Similar to proposals using 60 GHz DCNs [7], Arnon suggests arranging racks in circular cells such that neighboring racks can communicate using LOS links. Moreover, ToRs within a cell can communicate with Aggregate (or core) switches located at a higher layer as shown in Figure 3. Aggregate (or core) switches can communicate with each other at a higher layer on top of the layer of ToRs. However, a complete topology of a DC using the proposed cell design has not been investigated.

III. EXISTING INDOOR FSO STANDARDS

In this section, we briefly discuss existing standards related to indoor FSO. Table II presents a brief summary of the characteristics related to the physical (PHY) layer of the standards discussed.

A. IEEE 802.11

The original version of the standard *IEEE 802.11* released in 1997 specifies two data rates of 1 and 2 Mbps to be transmitted via infrared (IR) signals or RF at 2.4 GHz [28], [29]. The peak-power wavelength of the transmitter is in the 850-950 nm band, while a typical link length is limited to 10 m. The IEEE 802.11 specification was developed for diffuse links [28]. A diffuse link utilizes the reflection of light from *diffusely* reflecting surfaces such as ceiling and walls. This improves the robustness of the FSO link especially with the existence of barriers, and allows user's mobility. However, the drawbacks exhibited by IR communication, such as, multipath-induced inter-symbol interference, difficult optical collision detection, and ambient light (natural and artificial), have prevented its implementation [29].

B. IrDA

IrDA developed six standards (see Table II) focusing on low cost, short-range, line-of-sight (LOS), point-to-point FSO links mainly for connecting handheld mobile devices with mobile devices or fixed docking stations [29]. IrDA standards include, Serial Infrared (SIR) with data rates ranging from 2.4 to 115.2 kbps, Fast Infrared (FIR) supporting 4 Mbps, and Gigabit Infrared (Giga-IR) which currently supports 512 Mbbs and 1.024 Gbps [29].

The targeted bit error rate (BER) is 10^8 for SIR-VFIR and 10^{10} for Giga-IR. The maximum link length is less than 1 m (or 20 cm for low-power implementations) in SIR-to-UFIR range of standards [29]. On the other hand, docking station is used for Giga-IR to guarantee beam alignment by limiting the maximum link length to 6 cm.

C. Visible light communication Association (VLCA)

Visible light communication (VLC) is another rapidly emerging technology in which light emitting diodes (LEDs) are used to provide VLC data links as well as illumination. In 2006, members of VLC Consortium (VLCC) [the predecessor of VLCA] proposed the standards, CP-1221 (VLC System), and CP-1222 (Visible Light ID System) of Japan Electronics and Information Technology Industries Association (JEITA) [30]. In 2013, JEITA proposed the CP-1223 (Visible Light Beacon System), which is a simplified and improved version of CP-1222, to TC-100 of the International Electrotechnical Commission (IEC) and was approved as IEC 62943 in 2014.

D. IEEE 802.15.7

In response to the advances in the VLC technology, IEEE proposed the *IEEE 802.15.7* standard. This standard defines PHY and medium access control (MAC) layers for short/medium range VLC links to support audio and video multimedia services. The IEEE 802.15.7 standard supports three types of PHY layers (see Table II) that can co-exist but not interoperate. Either PHY I or PHY II is required for all IEEE 802.15.7-compliant device. PHY III is developed for applications with multiple light sources/detectors, and thus a PHY III type device must also satisfy PHY II standard for coexistence [29].

IV. FSO LINKS IN DCS: THE CHALLENGES AHEAD

Emerging applications and technologies present new needs and opportunities for development of new standards. From Table II, it is clear that existing standards do not cover the technology, which is crucial for the evolution of DCs. For example, the IrDA standards that are developed for point-to-point FSO links are designed for short-range FSO links. Thus, these standards are not adequate for FSO links in DCs.

Even though it is expected that future IrDA standards will allow for higher data rate and link distances greater than 1 m, we believe that there are issues that must be considered during the design of FSO links for FSO-DCs. In the following, we discuss potential challenges that can arise during the standardization of FSO links for DCs. Moreover, we propose and discuss possible solutions for these challenges:

1) **High link capacity:** Applications hosted by DCs (e.g., Hadoop and Spark) generate large demands for bandwidth with intra- and inter-rack communication. High link and network capacity is crucial to meet such requirements. Existing IrDA standards supporting high data rate point-to-point links, such as Giga-IR, use docking stations, and thus link distance is limited to 6 cm. There is a need for standards to help accelerate the development of high data rate point-to-point links suitable for DCNs where link distance must range from one to few tens of meters.
2) **Security:** In a DC, often data is exchanged between nodes in different racks. This may create security problems that must be handled by isolating data from unintended nodes and services. One of the distinct advantages of FSO technology is its inherent PHY layer immunity to eavesdropping as compared to RF technologies. FSO link designers must take advantage of this feature and develop efficient low overhead security protocols at higher layers.
3) **Small form factor of networking components:** A typical rack is 0.078″ high, 23-25″ wide and 26-30″ deep. Servers and switches are inserted horizontally into the racks. The thickness of a module in a rack is measured in *Rack Unit (U)*, which is 1.8″. Most servers fit the 1U size, other servers may require 2U or larger sizes [22]. The designers are required to develop components and network interfaces of small form factor taking into consideration the dimension constraints imposed by DCN commodity technologies.
4) **Visible vs. infrared sources:** Point-to-point FSO links require careful installation and alignment [20], [21]. Using visible light sources can ease the alignment of FSO links in FSO-DC. However, most off-the-shelf components such as laser diodes (LDs) and optical modulators are manufactured for fiber optics, and thus operate in the infrared spectrum. This is because the attenuation of the glass in fiber optics is the lowest at the infrared region of the spectrum. With the evolution of FSO-DCs, there is a need for new standards to develop the components required for establishing point-to-point FSO links using visible light LDs such as optical modulators.
5) **Obstruction-free FSO Links:** The main challenge in designing an FSO-DCN is to establish *obstruction-free* FSO links. At the scale of mega DCs, DCNs interconnect hundreds or thousands of racks. Wireless network should scale to meet this large link connectivity requirements. Network resources must be efficiently provisioned to meet the requirements of hosted DC services and to maintain a minimum level of availability. For adjacent racks, FSO link can be placed on ToRs at a height that is above the average human height, so human movements do not obstruct the link [20], [21]. However, in order to connect arrays of adjacent racks or servers, other solutions such as FSO-Bus [2] or rearranging the racks in circular cells [12] may be needed.
6) **Agile FSO Links:** To address the hotspot problem encountered by wired DCNs, wireless links must have a degree of reconfigurability. As discussed in Section II, one of the main challenges faced by FSO-DC designers is establishing and maintaining FSO links between different nodes (servers/racks). Incorporating mechanical systems to establish wireless links [9] can add to the complexity and latency of the system, and increases risk of failure. Moreover, at the scale of mega DCs, it might be difficult to control the direction and altitude of hundreds of optical transceivers to ensure LOS connectivity. In order to do that, a central controller with global knowledge of traffic and current configuration of a DC is required. One of the main functions of such controller is to establish new LOS connections without affecting or blocking already existing LOS links. On the other hand, using selective pre-configured links may not fully utilize the flexibility provided by wireless links [10], [11]. New means for realizing agile configurable FSO links are needed. These new approaches may require changing the arrangement of racks within a DC instead of using conventional row-based configurations.
7) **Heat and air flow:** DCN designers must change the rack arrangement in DCN floor instead of using the conventional row-based arrangement to fully utilize the flexibility provided by wireless links. Any change in the DCN floor can cause changes in the air flow and heat distribution properties. This in turn can cause turbulence and may impact the performance of FSO link. Therefore, computational fluid dynamic (CFD) analysis must be performed for new DCN arrangements to understand the behavior of the air and heat flows and ensure functional and efficient FSO link design.

8) **Artificial light sources:** In the absence of the background radiation, ambient artificial light becomes the dominant source of noise for indoor FSO systems [2]. Conventionally, two types of ambient artificial light sources are used for indoor illumination, incandescent and fluorescent lights. Using high pass filters (HPF), fluorescent lights driven by a conventional ballast can be mitigated, whereas, fluorescent lights driven by electronic ballast are harder to mitigate .
   Due to the good attributes of LEDs, such as, better light quality, low energy consumption, small size, and long lifetime, there is a trend towards using LEDs to replace traditional incandescent and fluorescent light sources for indoor illumination [19], [31]. Since LEDs have narrower power spectral densities (PSDs) as compared to that of incandescent and fluorescent lights, a possible solution to mitigate the effect of the artificial ambient light in DCs is to illuminate the DC using LED sources that are out of band with respect to the LDs used in the DC for communication [2]. As mentioned earlier, LEDs are used for VLC communication. We envision that, not only LEDs can be used for illumination in DCs, but also it can be utilized for communication and networking (e.g., unicast/broadcast of control signals).
9) **Vibration:** In order to achieve high data rate links, point-to-point FSO links are used. However, point-to-point links require careful alignment so that sufficient optical power can be received. Vibrations due to server fans, discs, HVAC and UPS units [32] can lead to link misalignment. The effect of vibrations can also add to the complexity of the FSO link design. One approach to alleviate the effect of vibrations is to mount optical transmitters/receivers on a metal frame that is separate from the rack structure. This way, the impact of rack vibration is reduced. Links between the rack and the optical modules mounted on the frame can be established using short flexible optical fibre cables.

V. CONCLUSIONS

Currently deployed wired data center networks (DCNs) suffer from increasing hotspot and cabling complexity problems. This has motivated the researchers to investigate the feasibility of using wireless technologies in the design of DCNs. In this paper, we review the state of the art of wireless DCNs using FSO. We also briefly review existing indoor FSO link standards. Existing indoor FSO standards may not be suitable for developing FSO links for DCNs. For example, IrDA standards are suitable for high data rate short FSO links, whereas, IEEE 802.15.7 standard and VLCA standards are suitable for short/medium range VLC low data rate links. We investigate and discuss challenges that may face FSO-DC designers, and identify standardization needs and opportunities to help develop FSO links for FSO-DCs. Standards for FSO links in DCN must take the high data rate and distance requirements, as well as effect of vibration into consideration.

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