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Wireless Communication in Data Centers: A Survey

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***Abstract*—Data centers (DCs) is becoming increasingly an integral part of the computing infrastructures of most enterprises. Therefore, the concept of DC networks (DCNs) is receiving an increased attention in the network research community. Most DCNs deployed today can be classified as wired DCNs as copper and optical fiber cables are used for intra- and inter-rack connections in the network. Despite recent advances, wired DCNs face two inevitable problems; *cabling complexity* and *hotspots*. To address these problems, recent research works suggest the incorporation of wireless communication technology into DCNs. Wireless links can be used to either augment conventional wired DCNs, or to realize a pure wireless DCN. As the design spectrum of DCs broadens, so does the need for a clear classification to differentiate various design options. In this paper, we analyze the free space optical (FSO) communication and the 60 GHz radio frequency (RF), the two key candidate technologies for implementing wireless links in DCNs. We present a generic classification scheme that can be used to classify current and future DCNs based on the communication technology used in the network. The proposed classification is then used to review and summarize major research in this area. We also discuss open questions and future research directions in the area of wireless DCs.**

***Index Terms*—Wireless data centers, 60 GHz, free space optical (FSO), optical wireless communication (OWC), data centers, data center network.**

I. INTRODUCTION

BIG DATA is a term used to describe high volume, high velocity, and/or high variety data sets [1]. Big Data applications can be found in disciplines like, social media, bioinformatics, Internet-of-Things (IoT), nanoinformatics, and real-time research analytic services. For example, it is expected that the Large Synoptic Survey Telescope (LSST), which will be deployed in Chile in 2016, will acquire around 10 Gbps for ten years resulting in a final disk storage and database size of 0.4 Exabytes and 15 Petabytes, respectively [2]. According to the International Data Corporation (IDC), the IoT market is expected to grow from 9.1 billion devices and objects connected to the Internet in 2013 to 28.1 billion by 2020 [3]. As the portfolio of bandwidth and computation intensive Big Data applications continues to grow, so does the demand for *mega data centers (DCs)* that support 100,000 servers and beyond [4].

A *DC network (DCN)* is the networking infrastructure that provides the intra- and inter-DC networking services. It is, therefore, essential to design an efficient high-speed/high-bandwidth DCN to meet the high computing and communication demands in DC. The design of a DCN must also satisfy several requirements such as scalability, low latency, availability, and minimum cost. Other practical concerns, including cabling complexity, power consumption, and cooling, must be also counted for in the design [5], [6]. Moreover, DCN design must be adaptable to respond to dynamically changing and evolving traffic patterns.

Figure 1 shows the widely used conventional hierarchical *tree-based DCN* architecture. Servers are stacked in racks that are arranged in rows. A Top-of-Rack (ToR) switch is used to perform intra- and inter-rack communications. A gateway router is used to connect the front end of the content and load balancing switches with the Internet. At the back end, the content and load balancing switches are connected to servers using two (core-ToR) or three (core-aggregate-ToR) layers of switches. Most DCNs deployed today use copper-cables and fiber optics for networking. As we move up in the tree, more powerful links and switches are used with oversubscription factors of 1:2 (or more at higher levels in the tree) impacting inter-rack communication [7]. Since switches and routers are primarily used for data forwarding and routing, conventional treelike DCN are classified as *switch-centric* DCNs.

Analysis of real world DCN traffic statistics shows that some applications (e.g., Hadoop [8]) do have unpredictable traffic patterns and unbalanced traffic distributions [7], [9]–[13]. Hadoop is one of the widely used implementations of MapReduce [14], which is a distributed processing framework for large datasets. Distributed systems use data replication to offer scalability and availability of data. For example, a file written to Hadoop Distributed File System (HDFS) is split into smaller data blocks that have configurable size. To ensure availability and scalability, Hadoop randomly distributes three replicas of each data block among distinct nodes housed in different servers, in the network [15], two of which are on the same rack to reduce inter-rack communication. A node requires a combination of local (intra-rack) and remote (inter-rack) data access to complete a task. Therefore, applications hosted by DCNs generate large demands for bandwidth with different communication patterns involving a combination of unicast, multicast, in-cast, and all-to-all-cast traffics [4], [16]. For example, Hadoop requires in-cast traffic delivery during the shuffle stage of MapReduce, and requires multicast for data replication, parallel database join operation, as well as data dissemination in virtual machine (VM) provisioning [16].

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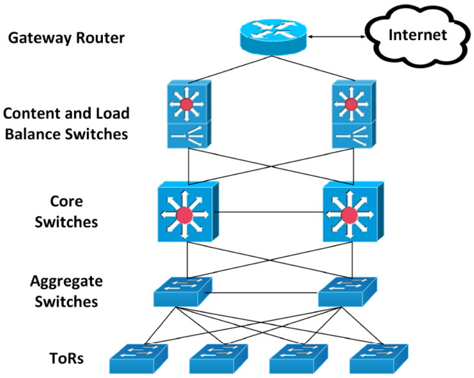


Fig. 1. Conventional hierarchical tree-based DCN architecture.

Certain nodes in a DCN may contain data blocks that are required by many jobs. Such nodes are referred to as *hotspots* [12], [13], [17]–[19]. It is difficult for tree-based DCNs to adapt to unpredictable traffic patterns resulting from hotspots due to the fixed hierarchial topology and link oversubscription. Inadequate network capacity and oversubscribed links can lead to flow congestions. This in turn can cause increased programming effort and reduction in concurrency of execution of applications, and thus overall network performance degradation [13]. In addition to the oversubscription problem and inability to adapt to hotspots, conventional tree-based DCNs may suffer from limited scalability, high cost, high energy consumption, and low cross-section bandwidth [20].

The problems encountered by tree-based DCNs have motivated researchers to explore new DCN architectures. During the last decade, the research community have exerted a greater effort to appease the oversubscription problem by using Clos toplogy to design switch-centric DCNs (e.g., Fat-Tree [21], VL2 [17], and PortLand [22]). Clos-based DCN architectures can be easily deployed incrementally and can also evenly distribute the network load across all the links [23]. However, large number of switches is required in Clos-based DCNs leading to limited scalability and lower cost-effectiveness [23].

Unlike switch-centric DCNs, servers in *server-centric* DCNs are used for both computation and routing or relaying of data to other servers. Therefore, less number of switches is needed. Several proposals investigate the viability of server-centric DCNs by developing recursively defined DCN (e.g., DCell [24], BCube [25], FiConn [26], DPillar [27], and BCN [28]) or using a fixed topology DCN (e.g., CamCube [29] which uses torus topology). Most server-centric DCNs have improved scalability and cost-effectiveness as compared to most switch-centric DCNs [24]–[28]. Due to their recursive construction procedures, many servers in server-centric DCNs are in close proximity of each other. Thus, server-centric DCNs have the locality of servers property that can be utilized to improve communication efficiency and VM placement [23]. This performance improvement, however, is achieved at the cost of higher cabling and implementation complexities and possibility of unevenly loaded links [23]. Moreover, servers are not designed to route and forward data traffic, and thus server-centric DCNs may not be suitable for high-volume and high-speed data traffic [30], [31].

Current trends in high-speed/high-bandwidth DC applications show that the hotspot problem is likely to worsen in the future [32]. Since it is difficult to predict the demand for each rack, and in order to accommodate the worst case scenario, an over-deployment of copper and optical fiber cables is needed. Therefore, available DCN designs offer little or no cost-performance tradeoffs. On the one hand, low-cost designs sacrifice performance, on the other hand, only over-provisioned high-cost designs offer reasonable performance.

Recent real world DCN traffic traces show that more than 95% of the data are being transferred by the top 10% largest flows [33]. Thus, oversubscribed DCN with interconnects that can support elephant flows (i.e., flows with large amount of data) may be more favorable than over-provisioned DCNs that guarantee full bisection bandwidth between large number of pairs of servers across the DCN [33], [34]. This motivated the researchers to investigate the feasibility of establishing wired or wireless on-demand links to support elephant flows in oversubscribed DCNs as a different approach to tackle the hotspot problem [7]. It is worth pointing that, no matter what technology is used, connecting hundreds or thousands of nodes in a DCN is going to be problematic.

In case of wired on-demand links, commodity electrical switches are deployed to connect a subset of nodes and provide on-demand wired links when needed. However, electrical interconnects used by most existing DCNs are increasingly becoming a bottleneck as using optical fiber cables requires optical-electrical-optical (O-E-O) conversion at every port of the interconnect [33]. Therefore, researchers started to investigate the use of optical interconnects in DCNs developing hybrid wired (electrical + optical) DCNs [34]–[38]. Similar to electrical switches, hybrid DCNs can be hierarchical tree-based switch-centric (e.g., HyPaC [39], Helios [40], and Proteus [34]), or recursively defined server-centric (e.g., HyScale [33], [41]).

The advantage of realizing wired on-demand links is that the realized links are consistent with the original wired DCN. However, for efficient operation, the network used to realize the on-demand wired links must interconnect the nodes that are predicted to encounter the hotspot problem, otherwise, the problem remains unsolved. At the scale of mega DCNs, it can be difficult to predict nodes susceptible to hotspot problem. Moreover, wired solutions require the deployment of larger number of cables which may escalate *cabling complexity* problems (e.g., cable management, maintenance, and heat dissipation).

A typical DCN employs various types of cables (e.g., coaxial, UTP, and optical fiber) for different purposes. The design and development, as well as maintenance and repair of different cabling infrastructures at the scale of buildings, require significantly high capital investment, as well as high operational cost [13], [18]. Cable infrastructures can lead to inefficient space utilization [18], [42], and inefficient cooling and thus higher energy consumption due to restricted airflow caused by thick cable bundles behind/between racks, as well as under raised floors [42]. Moreover, modifying deployed networks can be costly and complex especially for hierarchial network topologies. For example, in order to double the number of ToRs in a Clos-based DCN, half the existing cables must be rewired or twice the required higher-stage network switches must be pre-deployed [18].

Cabling complexity can be partially alleviated by developing cabling infrastructures based on structured cabling techniques. Although these techniques can help achieve a tradeoff between cabling and server densities, cabling complexity remains a major problem [42].

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 [6], [7], [13], [17], [18], [32], [43]–[59]. There are two candidate wireless technologies, radio frequency (RF) and free space optics (FSO), also known as optical wireless communication (OWC). In case of RF, researchers focus on 60 GHz RF technology since it stands out from other RF technologies due to its short range and high bandwidth. In FSO communication, a modulated light beam propagates in free space with no fibers involved. Therefore, FSO combines the flexibility of wireless communication, and the high-speed/high-bandwidth of optical communication.

A. Motivation and Scope

Most existing DCNs can be classified as wired DCNs in which copper and fiber cables are used for networking. Wired DCNs received an increasing attention in the DCN research community evident by the increasing number of papers and surveys that discuss, analyze, and motivate new developments in wired DCNs (see for example [20], [60]–[62]).

As discussed earlier, the need for developing adaptive DCNs has motivated the research community to investigate the feasibility of incorporating wireless technologies in DCNs. As a result, several research papers on wireless DCNs have been published.

A few recent survey papers on wired DCNs only briefly discuss the deployment of 60 GHz RF technology in DCNs [20], [60], [62]. On the other hand, a recent survey paper that exclusively focuses on the topic of wireless DCNs was published early 2015 [63]. Similar to the survey papers on wired DCNs [20], [60], [62], Baccour et al. [63] focus their discussion only on deploying the 60 GHz RF technology in DCNs. In [64], we focus our discussion on DCNs using FSO. We analyze existing indoor FSO standards and the challenges that may face the DCN designers. We also identify standardization needs and opportunities to help accelerate the development of FSO links for DCNs.

From the above discussion, we make the following observations:

1) DCN design space is reshaping as new technologies for networking are deployed, and there is a current need to rethink the design philosophy of DCNs. Therefore, a classification scheme that can formally express the changes in the DCN design space is required to help identify new DCN designs.
2) Deploying 60 GHz and FSO technologies in DCNs encounter different design requirements and challenges. However, as we will show in Section II, there are many similarities between the two wireless technologies. Therefore, we believe that the development of DCNs using one of the technologies can significantly benefit from the other.

In the absence of a systematic description of the DCN design space evolution, it can be difficult for researchers to fully explore the DCN design space and identify potential designs. This motivates us to develop a new survey to collate and present current advances in wireless DCNs in a systematic fashion to facilitate the sharing of knowledge among researchers using different wireless technologies to develop wireless DCNs. We propose a classification that can be used to classify existing and emerging wired and wireless DCNs. Based on this classification, we survey current state of the art of wireless DCNs. We review the requirements, challenges, and trends using 60 GHz RF and FSO technologies. The proposed classification leads to a nearly complete picture of the design space for DCNs. This help us to identify potential unexplored solutions for next-generation DCNs.

B. Notations

Lasercom, OW, or FSO are three names used to refer to fiber-less optics technology in the literature. However, fiber-less optics and lasercom are rarely used nowadays. Even though it is not a rule of thumb, it has been noticed that OWC is used to refer to indoor fiber-less optic systems, whereas, many publications use FSO to refer to outdoor point-to-point fiber-less optic systems. Since both names (i.e., FSO and OWC) refer to the fiber-less communication systems disregard the environment in which the link is established, and taking into consideration the fact that both terms have been widely used in the literature, we use both terms interchangeably in this survey paper.

To improve the readability of the paper, we summarize all acronyms and abbreviations used in Table I.

C. Paper Organization

The remainder of this paper is organized as follows. In Section II., we discuss the basics of wireless communication and candidate wireless technologies in DCNs. We dedicate Section III to discuss the proposed DCN classification. In Section IV, DCNs employing RF technology are discussed followed by a discussion on DCNs using FSO in Section V. Challenges and potential solutions of wireless DCNs are analyzed in Section VI. We investigate open problems, future research directions in the area of wireless DCNs in Section VII. Finally, a summary is given in Section VIII.

II. POTENTIAL WIRELESS TECHNOLOGIES IN DCNS

In this section, we discuss two candidate wireless technologies, 60 GHz RF and FSO, that can be used in wireless DCNs. We compare their attributes, advantages, and disadvantages. We also compare FSO and optical fiber since they both are optical technologies. For the sake of completeness, we first give a brief introduction on wireless communication systems.

TABLE I
ACRONYMS AND ABBREVIATIONS

Acronym	Description
5G	5^{th} Generation of Wireless Communication Systems
BER	Bit Error Rate
CATV	Cable Television
CG	Cayley Graph
DC	Data Center
DCN	Data Center Network
DD	Direct Detection
ECS	Electrical Circuit Switching
EPS	Electrical Packet Switching
FCC	Federal Communications Commission
FOV	Field of View
FSO	Free Space Optical
GA	Genetic Algorithm
IM	Intensity Modulation
IR	Infrared
ISM	Industrial, Scientific and Medical
LD	Laser Diode
LED	Light Emitting Diode
LOS	Line of Sight
MAC	Medium Access Control
NLOS	Non-Line of Sight
OOK	On-Off Keying
OW	Optical Wireless
OBS	Optical Burst Switching
OCS	Optical Circuit Switching
OPS	Optical Packet Switching
PD	Photodetector
PSD	Power Spectral Density
RF	Radio Frequency
SAS	Shortlex Automatic Structure
SNR	Signal to Noise Ratio
ToR	Top-of-Rack
UTP	Unshielded Twisted Pair
UWB	Ultra-wideband
WO	Wireless Optical
WTU	Wireless Transmission Unit

A. Basics of Wireless Communication

Wireless communication is one of the active areas of research in the communication field today. In wireless communication, information is transferred from the transmitter to the receiver without the need for a confined medium (e.g., cable). Figure 2 depicts part of the electromagnetic (EM) spectrum. The wavelength of a signal decreases as the frequency increases and different frequencies across the EM spectrum have different propagation properties. According to Friis law, the effective area of an antenna decreases as frequency squared.

Audio frequencies extend from 3 kHz to 20 kHz in the very low frequency (VLF) band, whereas radio frequency (RF) occupies a very wide range of spectrum (20 kHz - 3 THz). Depending on the nature and requirements of the application, a suitable carrier RF frequency is selected. For example, radio waves have limited propagation capability in electrical conductors such as salt water due to absorption, and thus very long wavelengths (i.e., very low frequency and very large antenna) is required. Therefore, ground-to-submarine communications utilize audio waves, or RF in the VLF band which can penetrate only up to 20 meters below sea surface. On the other hand, IEEE 802.11b/g/n (WiFi) wireless local area networks require worldwide compatibility and moderate capability of penetrating windows, walls, and ceils. Therefore, the unlicensed 2.4 GHz UHF and 5 GHz SHF industrial, scientific, and medical (ISM) radio bands are utilized to realize short and medium range links in homes and offices.

When the term wireless communication is mentioned, conventionally, RF technology is the first to come to mind since it is a well-developed mature technology. However, recent advances in FSO technology have narrowed the gap between FSO and RF technologies. FSO technology can operate in a wide range of spectrum, including invisible infrared spectrum (used by optical fiber technology), visible light, and ultraviolet [65]. This helped FSO to be successfully used in a wide range of applications. Examples of applications in which FSO technology has already found its place are, mobile networks backhaul [66], space communication [67], underwater sensing [68], and wireless sensor networks [69]. Moreover, it is envisioned that the 5G wireless communication systems will incorporate several complementary access technologies along with the RF technology, including FSO [70].

B. 60 GHz RF Technology

Millimeter wave (mmWave) RF communications operating in the millimeter band (30-300 GHz) is rapidly advancing. Most of the current research is focused on the 60 GHz band and the E-band (71-76 GHz and 81-86 GHz) [7], [17], [71], [72]. The unlicensed spectrum of the mmWave communications makes it possible to launch products world-wide. Moreover, the extremely high frequency and the large spectrum of the mmWave band allow for high bandwidth short range links. The characteristics of the mmWave communications urged the researchers to consider the mmWave RF technology in the next generations of wireless communication systems (e.g., 5G) to provide multi-gigabit communication links [73].

The 60 GHz band is a 7 GHz wide unlicensed band of spectrum (57-64 GHz). Although unlicensed, recent standards, such as IEEE 802.11ad are developed to standardize very high data rate transmission at 60 GHz. Operating at 60 GHz has unique characteristics compared to other RF technologies, such as the ISM band at 2.4 GHz and ultra wide-band (UWB), for providing link connectivity in DCNs [7], [17], [42]. For example, the bandwidth of the 60 GHz band is 88× that of the ISM band at 2.4 GHz (80 MHz wide) which supports the IEEE 802.11b/g/n (WiFi) networks [7].

The large available spectrum in the 60 GHz range allows for a large number of independently operating directional links. Moreover, advances in modulation and coding techniques help improve spectral efficiency, and thus, even larger number of links can be provided using the same bandwidth. For example, a 1 Gbps link can be achieved using 100 MHz channel and spectral efficiency of 10, that is 70 orthogonal channels using the 7 GHz bandwidth of the 60 GHz technology. This large number of channels, along with careful design can provide the level of scalability required for wireless mega DCN.

The high frequency of 60 GHz facilitates compact antennas with high gain. For example, a one-square inch (6.5 cm^2) antenna can provide a gain of 25 dBi at 60 GHz. Moreover, short wavelength of 60 GHz enables the design of sophisticated

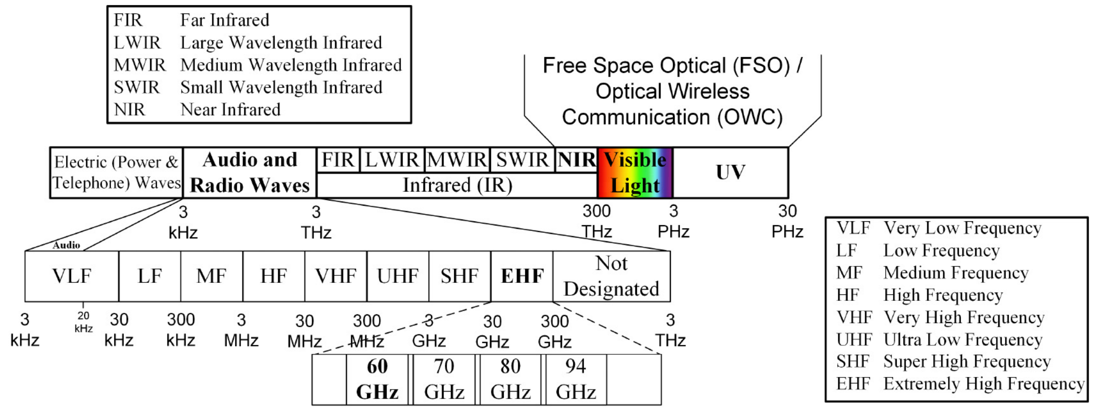


Fig. 2. Electromagnetic Spectrum.

interfaces and the use of phase array antennas with a large number of elements of very small form factors [42]. Increased number of antenna elements in a phased array helps achieve highly directional beams with small footprints, thereby increasing the number of simultaneous transmissions.

C. FSO Technology

The absence of atmospheric impairments in addition to other attractive attributes of indoor FSO links make FSO a strong candidate wireless technology to be used in future wireless DCNs. A simple FSO link consists of a light source at the transmitter, and a photodetector (PD) at the receiver to detect the received light.

Light Emitting Diodes (LEDs) and Laser Diodes (LDs) are the most commonly used light sources in FSO links [74]. LDs are highly directional sources that have high optical power outputs and broader modulation bandwidths [75], and therefore, can support high data rate transmission. On the other hand, LEDs are large-area emitters and are considered as extended sources that can be operated safely even at relatively high powers. LEDs are cheaper and more reliable as compared to LDs, and thus, are preferred in some indoor applications. In general, LEDs support lower data rates as compared to that of LDs [75], however, recent research demonstrations show relatively high achievable data rate (up to 3 Gpbs) using LEDs [76], [77].

Positive-intrinsic-negative (PIN) or avalanche photodetectors (APDs) are widely used to detect the light beam at the receiver [74]. PIN photodetectors are cheaper, operates at low-bias, and can tolerate wide temperature fluctuations [74]. Therefore, PIN photodetectors are used in many commercial infrared links that requires FSO links of low cost, and low data rates. APDs are essentially PIN photodetectors that are operated at very high reverse bias resulting in internal electrical gain [78]. APDs are favorable and have superior performance compared to PIN PDs when the ambient light noise is little. APDs are used in systems that require high data rates and high performance in general. Extensive research effort is being exerted in the field of quantum dot, Nano-particle and graphene-based PDs to develop ultrafast PDs that operate over a broad range of wavelengths [79]–[85].

Although On-Off keying (OOK) is the most commonly used modulation scheme due to its simplicity, wide range of digital modulation schemes can be used in FSO systems. Pulse Position Modulation (PPM) or one of its variations, such as Variable-PPM (VPM), is usually used in high data rate applications (e.g., deep space communication) [68], [74], [86]. Both OOK and PPM are classified as single-carrier pulsed modulation. Multiple-subcarrier modulation, such as Orthogonal frequency-division multiplexing (OFDM), can also be used in severe channel conditions since it does not require complex time-domain equalization as compared to PPM [87].

D. 60 GHz Versus FSO

A comparison of indoor 60 GHz RF and FSO technologies is presented in Table II. Both technologies occupy unregulated band of the spectrum. Therefore, operating using FSO or 60 GHz does not require approval allowing manufacturers to develop worldwide compatible components.

It is expected that the components of the 60 GHz technology will be inexpensive since standard 90nm CMOS technology is used for developing components of the 60 GHz technology with small form factors. On the other hand, most exiting commercial FSO devices are developed for outdoor long range FSO links. Therefore, FSO transceivers are housed in bulky packaging and are sophisticated to endure atmospheric impairments, including rain, fog, wind, and building sway. In indoor FSO links, however, this level of complexity is not required. It is possible to realize an indoor FSO link by using the output light from a single-mode fiber (SMF) or multi-mode fiber (MMF) and collimator. At the receiver, a collimator is used to couple the received light to the receiver SMF (or MMF) [56], [88], [90].

RF technologies can offer high data rates when high carrier frequencies are used. At high-frequencies (i.e., short wavelengths) [91], diffraction and reflection barely apply. However, non-line of sight (NLOS) RF communications highly depend on the diffraction and reflection of signals. Therefore, 60 GHz links become line-of-sight (LOS) links, and the key features of RF technologies, such as coverage, ability to penetrate obstacles, and receiver sensitivity, become less clear [74]. Although this can be considered as a limitation for RF technologies operating at high carrier frequencies, that is not necessarily the

TABLE II

Comparison Between 60 GHz RF and FSO Wireless Technologies for DC Application.

Property of Medium	60 GHz RF	Indoor FSO	Implications & Comments
Bandwidth Regulated?	No	No	• Approval not required. • Worldwide compatibility.
Obstacle Penetration?	Yes (very limited)	No	• Good security attributes for FSO and 60 GHz technologies. • Limited coverage, and thus LOS point-to-point links are required.
Radio Frequency Interference	Yes	No	• FSO has better frequency reuse • Higher Overall System Capacity using FSO.
Path Loss^a	High $\approx$ 68 dB for 1 m $\approx$ 91.5 dB for 15 m	Low $\approx$ 0 dB for 15 m	
Range/Coverage	Short ($\leq$ 15 m)	Medium ^{b} ($\leq$ 100 m)	Suitable for DC's confined space
Dominant Noise	Interference and thermal noise	Ambient artificial light	
SNR Proportional to	Signal amplitude	Signal power	High transmitter power requirement by FSO systems.
Technology Cost	Potentially Low	Potentially Low	

case for 60 GHz technology in DCNs. In fact, having limited coverage and being unable to penetrate obstacles are among the factors that motivated researchers to consider 60 GHz for DCNs. In DCNs, racks are arranged in close proximity, therefore, short range links are required. Moreover, the inability to penetrate obstacles can help reduce the complexity of dealing with interference and security issues. Similarly, in indoor applications, FSO link is confined to the room in which the system is installed due to the inability to penetrate physical objects so it can not be detected outside, securing transmissions against eavesdropping. Accordingly, the complexity of security measures and data encryption needed for using FSO and 60 GHz technologies can be reduced leading to simpler design process and less overhead.

The channels in 60 GHz technology are wider than that at 5 GHz, and thus, for a given link distance, the path loss is 20 dB higher than that at 5 GHz. Moreover, the 60 GHz band includes the absorption frequency of the oxygen atom. At 60 GHz, the signal-to-noise ratio (SNR) is roughly 55 dB worse than that of links at 2.4 GHz [44]. Therefore, 60 GHz technology has lower practical bandwidth than what is theoretically achievable. High path loss and link instability in 60 GHz technology can be alleviated using highly directional beams which can be realized using beamforming [42], [92]. Compared to RF, FSO inherently provide significantly higher bandwidth as compared to that of current RF technologies due to the large band of unregulated frequency. Moreover, FSO exhibit lower power attenuation, and thus, can offer higher data rates at short, medium, and long distances [74].

Radiation patterns of RF communication impose additional restrictions on the activity of wireless modules in close proximity to avoid interference [57]. Although it is less significant in 60 GHz technology, especially if beamforming is used, interference can increase the complexity of routing and network management schemes, and may thus reduce the overall throughput of the network. Moreover, using 60 GHz in a DCN full of metal structures can make the problem of interference more challenging [17], [93]. On the other hand, interference does not form a serious problem in case of FSO technology since point-to-point FSO links are used to achieve higher data rates [94]. This, however, means that FSO link requires accurate and stable alignment to maintain the link. As we will discuss in Section VI, vibrations due to server fans, discs, HVAC and UPS units may cause link misalignment adding more challenges to the design of FSO links in DCNs.

Intensity modulation with direct detection (IM/DD) is usually employed in FSO links. The high carrier frequency and the relatively large detector area provide spatial diversity that averts multipath fading. On the other hand, RF links experience signal magnitude and phase fluctuations due to reflections. Therefore, the design of FSO links can be simpler than that of RF. However, FSO receivers have lower sensitivity as compared to that of RF due to the speed limitations of the photo-electric conversion mechanisms [95].

The advantages of the 60 GHz RF technology motivated Ramachandran et al. to propagate the idea of using 60 GHz RF technology in DCN design [42]. Following their work, considerable research has been devoted to investigating the feasibility of deploying 60 GHz RF technology in DCNs [18], [32], [44], [48][51], [96]. Similarly, the advantages of FSO technology and its successful use in a wide range of applications has motivated researchers to investigate the use of FSO in the design of DCNs [6], [56]–[59].

E. FSO Versus Fiber Optics

FSO and optical fiber are two optical technologies providing comparable transmission bandwidth. Considering the similarities between FSO and optical fiber, we believe that it is important to compare the two technologies.

It might be noted that the advantages (disadvantages) of a technology may become less or more significant depending on the scenario in which the technology is deployed. For example, since we focus our discussion on the indoor DCN application, the capability of extending optical fibers for long distances becomes insignificant. On the other hand, complexities associated with laying fiber cables in an outdoor network, including permissions and digging, is absent in DCNs. Similarly, environment impairment, that is considered a major challenge for outdoor FSO links, becomes negligible in environmentally controlled mediums such as in DCNs.

Optical fiber technology uses a confined medium (i.e., fiber cable) for transmission, and thus optical fiber technology is immune to interference. However, according to optics and laser physics, light beam propagating in an optical fiber can suffer from chromatic and polarization mode dispersions, birefringence, scattering, and absorption [97].

In an FSO link, the light propagates through an unconfined medium (i.e., air). The absence of the confined transmission medium in FSO makes it, unlike optical fiber, insusceptible to chromatic and polarization mode dispersions, and birefringence. Moreover, light in fiber cables propagate by the mean of total internal reflection. Therefore, light beam in FSO can be around 1.5 times faster than that of in optical fiber resulting in lower propagation delay for FSO [57]. Nonetheless, unconfined mediums lead to beam divergence and make FSO links vulnerable to interference.

Fiber cables can be extended in overhead or under raised floor between any two racks in DCNs regardless of the physical arrangement of racks in the DC. Although this implies that there are no restrictions on the physical layout of a DCN, extending fiber cables require careful planning and time to ensure that installation standards are met. Specialized manpower is needed to adhere to installation recommendations, such as maximum bend radius and vertical rise, planning of cable routes, protection against impacts, and maximum tensile loading during the pull of the cable [98]. Unlike fiber optics, FSO links are point-to-point LOS/NLOS links, and thus require careful layout design to ensure feasible link alignment. This can lead to network layout design complexity. Once designed, FSO links do not require extensive setup planning or specialized personnel for installation as compared to fiber optics, and thus FSO links can be installed in a shorter time [99]. However, as discussed earlier, careful alignment and stability are required to maintain the FSO link.

In case of damage or failure, replacement or repair of a damaged fiber cable can be time consuming since cables are usually bundled. On the other hand, if an FSO transceiver fails it can be replaced as quickly as it was originally installed.

III. PROPOSED CLASSIFICATION OF DCN ARCHITECTURES

DCN architectures are broadly classified into *switch-centric* [21], [22], [100] and *server-centric* [25], [27], [28], [101] architectures. In switch-centric DCNs, servers operate only as computing nodes and switches are used for data routing. In server-centric DCNs, servers perform both, computation and data routing.

Wired DCNs are commonly classified based on switching schemes into three classes (see Figure 3); namely, electrical (circuit or packet switching), optical (packet, circuit, or burst switching), and hybrid [20], [38], [62], [102].

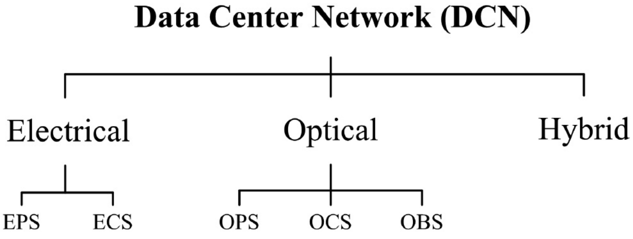


Fig. 3. Classification of conventional wired DCNs.

Wireless communication is a promising flexible approach that can help addressing the nondeterministic unbalanced traffic distribution of DCN applications and help alleviate congested hot spots [6], [17]. Wireless communication technologies can be used in DCNs by either *augmenting* already existing wired infrastructure with additional inter-rack wireless links, or by completely replacing the wired infrastructure by a *pure* wireless network. In the latter, wireless communication links are used to perform intra and inter-rack communications.

Augmenting wired DCNs with wireless links can solve the problem of hotspots; however, the wiring complexity problem remains unsolved. On the other hand, realizing a pure wireless DCN is expected to solve the hot spot and wiring complexity problems.

As wireless communication is finding its place in DCNs, we believe that a new classification is needed in order to include the emerging new DCN models. We identify four types of communication technologies that can be used in DCNs, wired (electrical cables and optical fiber) and wireless (RF and FSO). We classify DCNs based on the used communication technologies. Figure 4 depicts the proposed classification with all possible DCN design schemes based on the four communication technologies.

From Figure 4, DCNs can be broadly classified as Pure or Hybrid. Several DCN designs can fall under the broad hybrid class. In the following we formally define different types of DCN designs:

- **Pure Wired/Wireless DCN:** refers to a DCN in which a single (wired or wireless) communication technology is used for intra and inter-rack communication. This can result in a pure electrical/optical/RF/FSO DCN.
- **Hybrid DCN:** refers to a DCN that utilizes two or more technologies.
- **Hybrid Wired DCN:** is a DCN that deploys two or more wired technologies. This refers to a DCN in which electrical cables and optical fibers are used.
- **Hybrid Wireless DCN:** a DCN that uses two or more wireless technologies. A hybrid wireless DCN refers to a DCN in which RF and FSO are used for communication.
- **Hybrid (wired + wireless) DCN:** Refers to a DCN that deploys at least one wired technology and augmented with at least one wireless technology. This can lead to six types of hybrid DCNs:
  1) Pure Electrical + RF
  2) Pure Optical + RF
  3) Hybrid wired + RF
  4) Pure Electrical + FSO
  5) Pure Optical + FSO
  6) Hybrid wired + FSO

In Figure 4, for the sake of brevity, we only show Hybrid wired augmented with RF and Hybrid wired augmented with FSO DCNs. Dashed line indicates that we can further break it down to more categories as discussed above.

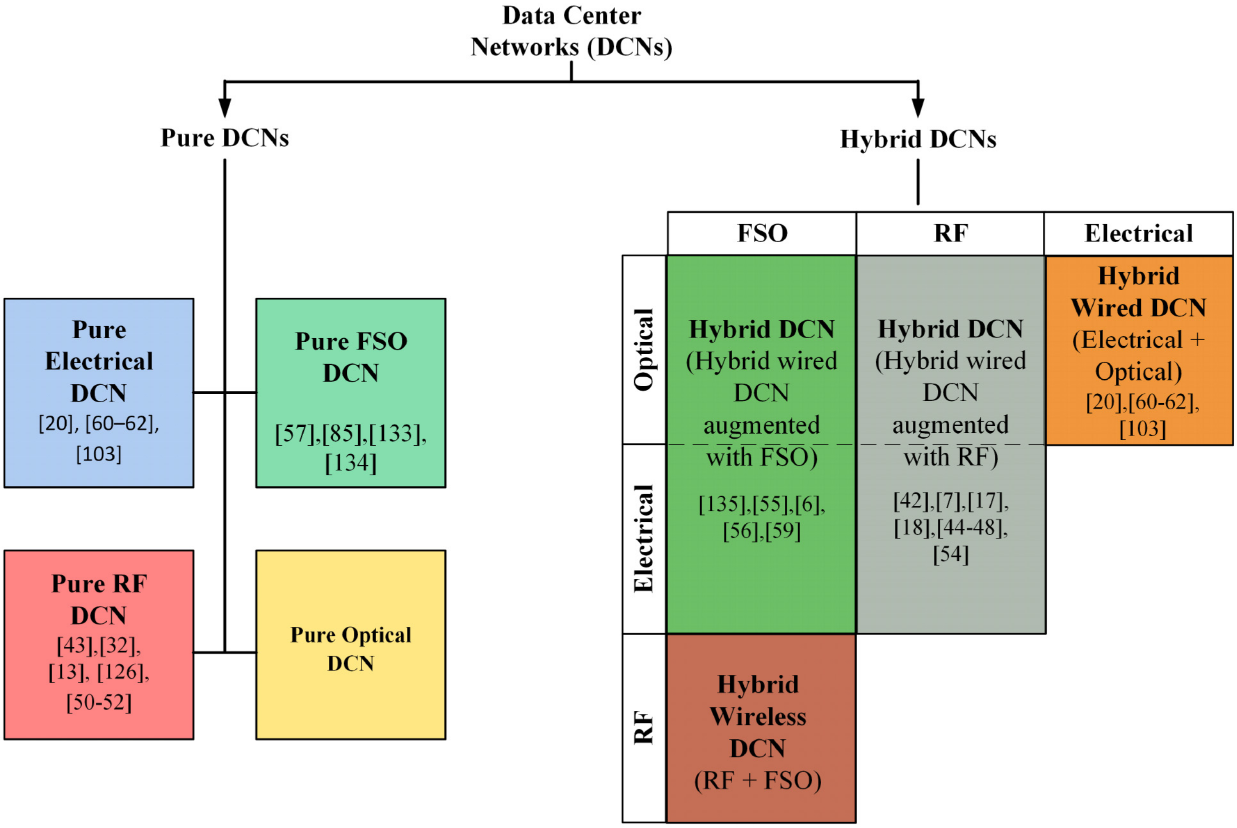


Fig. 4. Proposed data center network (DCN) classification.

It might be noted that, using the proposed classification, an electrical/optical DCN in conventional classification can be classified as a pure electrical/optical DCN, respectively. On the other hand, a hybrid DCN in conventional DCN classification falls under the hybrid wired DCN class.

For the sake of completeness, in this section, we briefly discuss wired-based DCNs. However, since wired DCNs are not the main focus of this survey paper, we refer interested readers to a selected list of recent comprehensive surveys that investigate research and development in the field of wired DCNs. Figure 4 is also populated with selected references.

Pure electrical DCN or simply *conventional DCN* is the most commonly deployed type of DCNs [20], [38], [62], [102]. Conventional DCN was first known as *server room*, which is a small room owned by a company. In a server room, a collection of servers are co-located and connected via an electrical network to serve the computational and storage needs of the company. Having large number of machines co-located in the same room requires good management and operation to guarantee their functionality. For example, it requires proper temperature and humidity control. Also, specialized personnel are needed in order to monitor and maintain the server room.

As companies increased in size, bigger rooms were needed. Fulfilling the requirements of expanding the server room requires large investment to cover the replacement of old networking components (servers, switches, etc.). A few companies were able to perform these changes, while for others it was an overhead too big to handle. The buildings equipped with a large network of servers in big companies started to be known as DCs. Small companies begun to outsource their computational and storage needs by using the DCs of big companies. This helped them avoid the huge costs of maintaining server rooms.

As mentioned earlier, it has been widely believed that to appease the ever increasing demand of high-bandwidth communication in DCs, DCN architectures must guarantee full bisection bandwidth between a significant number of servers [35], [40], [103]. However, according to empirical studies of DC traffic, it has been shown that 80% of the flows are mice flows (smaller than 10 KB in size) and 95% of the bytes transferred in a DC are in the top 10% of the elephant flows (flows with large amount of data) [9]–[11], [104]. Thus, full bisection bandwidth between more than a few pairs of servers at any instant is rarely required in a DCN [35], [39], [103], [105].

The limitations on electrical interconnects [34], [41] along with the existence of elephant flows have motivated researchers to consider *Hybrid wired DCNs*, where electrical and optical networks are utilized to perform inter-rack communication. In this scenario, optical networks are used to provide high-speed, on-demand, high bandwidth inter-rack communication in DCNs [35], [39], [40], [103], [105], [106]. Existing hybrid wired DCNs (e.g., c-Through and Helios) employ Electrical Packet Switching (EPS) and Optical Circuit Switching (OCS) technologies, respectively, for supporting bursty and long duration large flows in DCNs [34], [35], [39], [40], [107].

The need for EPS in DCNs is driven by the high switching time involved in OCS technologies [40]. However, the use of

EPS may somewhat restrain the exploitation of the advantages of photonics in DCNs [103]. EPS already started to become a bottleneck in large scale DCNs, especially with the increasing demand for high-speed, high-bandwidth links. With the recent progress in optical technologies [108]–[110], Optical Burst Switching (OBS) has been propagated as a good candidate for burst communications in data-intensive cloud applications [4], [33], [41], [111]–[116]. The use of OBS technologies in DCNs, however, has not yet received much attention.

Recent papers suggested the use of all-optical inter-rack communication instead of combining electrical and optical components [34], [106], [117]–[121]. It might be noted, however, that intra-rack communication is realized using electrical switching. This is because, traditional electrical cables (e.g., 10 GigE) are viable for distances below 10 meters (i.e., intra-rack communication) [120]. Moreover, the prices of the enabling technologies of optical communications are relatively high as compared to that of commodity electrical networking elements. Therefore, the concept of a pure wired DCNs using optical fibers did not attract the designers of DCNs, yet.

In case of wireless communication, a wireless technology can be used for inter-rack communication only (augmenting links) or to replace the whole network (pure wireless DCN) including intra-rack communication. Therefore, we believe that it is important to distinguish between the all-optical inter-rack communication and all-optical DCNs (*pure optical DCNs*). According to this definition, pure optical DCNs do not exist, and DCNs that use all-optical inter-rack communication can be classified as *hybrid wired DCNs*.

It is also worth pointing that in most existing DCNs racks are arranged in row-based physical topology. Therefore, research is mainly concerned with changing the logical topology (i.e., connection of servers and switches). Using wired communication, it is possible to realize different logical topology over the standard row-based physical topology. On the other hand, due to the requirements and constraints imposed by wireless communication technologies, it is possible that both physical and logical topologies can be changed to realize new efficient DCNs.

IV. SUMMARY OF TECHNIQUES FOR ADOPTING 60 GHZ IN DCNS

In 2008, Ramachandran et al. nurtured the idea of using 60 GHz technology in DCNs [42]. The authors identify the requirements of a DCN and the problems encountered due to wires. They discuss the suitability and the challenges of the use of 60 GHz inside DCNs. Ramachandran et al. envision three complementary deployment scenarios for both intra and inter-rack communications (see Figure 5). An array of antennas is used in order to create directional beam with small beam width. For intra-rack communication, Ramachandran et al. suggest using a reflector to create indirect LOS links, whereas for inter-rack communication, LOS, indirect LOS, or multi-hop links can be used.

Following the proposal by Ramachandran et al., researchers have been investigating the effectiveness of 60 GHz RF links in DCNs [7], [13], [17], [18], [32], [43]–[54].

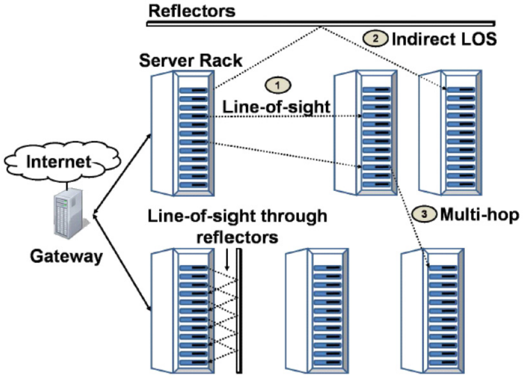


Fig. 5. Intra and inter-rack communications in 60 GHz wireless DCs as envisioned by Ramachandran et al. [42].

A. Hybrid RF DCNs

In [7], Kandula et al. propose the concept of *flyways* to tackle the hot spot problem. Flyways are on-demand stable multi-Gbps additional links (wired or wireless), added to wired DCN to provide additional capacity and alleviate the problem of hot spots at a fraction of the cost required to over-provision the DCN.

In case of wired flyways, additional switches are used to inter-connect random subsets of the ToR switches. On the other hand, wireless flyways can be achieved by placing one or more wireless transceivers atop each rack in the DCN. Wireless flyways provide more flexibility as compared to wired flyways. The authors formulate the wireless flyways placement problem and present a suboptimal algorithm in which a single flyway is added at a time. Preliminary results indicate that, using flyways can achieve a substantial improvement in the performance of the DCN with respect to the completion time of the demands (CTD). It is worth pointing that more wired flyways are needed as compared to wireless flyways in order to achieve the same overall improvement.

The work by Kandula et al. is preliminary and aim to understand the viability of adding on-demand links to solve the hot spot problem. Therefore, several assumptions made by the authors simplify the problem and overlook important aspects of the problem. For example, it is assumed that a 60 GHz module can communicate with other modules within its range of 10 m. Moreover, it is assumed that all flyways have the same capacity and the impact of interference is ignored.

In [44], the work on flyways by Kandula et al. [7] is extended. In this work, 60 GHz devices prototype is used. Performance measurement and simulation for 60 GHz link hardware, signal propagation, stability, interference, and TCP throughput are performed. Results indicate that directional 60 GHz links, are necessary for good link stability, interference avoidance and channel reuse, and higher throughput. The authors discuss three different models for establishing the flyways, namely, Straggler, Transit, and Greedy. In Straggler, a link is established between the pair of ToRs taking the longest time to complete. In transit model, indirect transit traffic is allowed using the room spared on a flyway in the Straggler model. Greedy model improves Transit model by picking the flyway that offloads the most traffic from bottleneck link. The proposed design is found to speed up DCN applications with predictable traffic workloads by 45% in 95% of the cases.

Compared to their preliminary work in [7], the authors have improved several aspects regarding their model and assumptions. However, the discussion still topology-independent and it is not clear how links will be realized between racks. Moreover, we believe that the model does not fully utilize the flexibility of the wireless communication to create configurable and agile links.

The work by Kandula et al. is classified as hybrid RF DCN since they adopt the 60 GHz wireless technology to implement wireless flyways. However, it is worth pointing that it is one of the major motivator for researchers to investigate the feasibility of wireless DCNs in general.

1) Wireless Channel Allocation: Cui et al. investigate the wireless channel allocation problem in hybrid 60 GHz DCNs [17], [45], [46], [122]. In their analysis, Cui et al. consider a wired DCN with hot spots. A separate 60 GHz wireless network is used to provide additional links and relieve the network. A rack is considered as a wireless transmission unit (WTU) with 60 GHz transceiver mounted on top of it. A wireless link is allocated to carry inter-rack traffic. Total transmission links form a wireless transmission graph. The authors adopt interference range model, in which a sender causes interference on the nodes inside its interference range. The problem of provisioning wireless links is formulated as an optimization problem with the objective function of maximizing the total utility of the wireless transmission. The utility of a link is defined in terms of the contribution to the global performance made by transmitting the traffic via wireless links. Genetic algorithm (GA) and greedy heuristic algorithm proposed by Cui et al. are used to solve the formulated optimization problem. Results show that using the wireless links improves the performance of the network with respect throughput and job completion. Results by Cui et al. confirm the effectiveness of using wireless communication to realize hybrid DCNs. However, the theoretical model used by the authors simplifies the problem and does not give a solid sense of the wireless channel allocation problem in real wireless DCN. For example, the model is topology-independent, in the sense that it is assumed that a WTU can communicate with any WTU in its range. This, however, is not true and great efforts are exerted by researchers to facilitate wireless communication in DCNs. Moreover, the used model ignores several aspects including the impact of reflections and metal structures on link interference.

2) Beamforming: Katayama et al. propose wireless packet-switching networking in DCs using steered-beam mmWave links [47]. Wireless transceivers are placed atop racks and LOS links between adjacent rows of racks are realized. Wireless transmission is limited to the adjacent row. Data packets are relayed via adjacent rows of racks wirelessly eliminating the need for long cables and additional switches, and without using long wireless links. Each node has a local routing table that stores routing information. The routing table is responsible of determining the next hop for the packet until the packet reaches its destination. A preliminary prototype of a mmWave steered-beam link combined with IEEE 802.11 control plane is demonstrated.

Katayama et al. do not carry out experiments to evaluate the proposed packet-switching DCN. However, since the proposed DCN is a short-range multi-hope network, one can expect that the DCN will show poor performance with respect to packet delivery latency.

Even though links realized using beamforming can help reduce interference, they still experience signal leakage. In packed small proximities such as in DCNs, this can significantly increase interference, and thus impact throughput.

In [48], Zhang et al. explore the feasibility of using 3D beamforming. They propose the use of 60 GHz wireless links that reflects off of a reflector mounted to the ceil of the DC as proposed by Ramachandran et al. [42]. The authors envision that this design is capable of addressing both link blockage and interference, thus improving overall transmission performance in DCNs.

A small 3D beamforming testbed is built by Zhou et al. [18] to demonstrate the ability of 3D beamforming in addressing both link blockage and link interference. Moreover, the authors propose a link scheduler. Using simulations, the authors show that wireless capacity and reach of 60 GHz links can be expanded using 3D beamforming as compared to that of 2D beamforming. A testbed is implemented.

Measurements confirm that using 3D beamforming, it is possible to realize 60 GHz links with zero reflection energy loss, reduced interference, and capability of avoiding obstacle that can block the beam. However, this comes at the cost of complexity of establishing the link. Moreover, the received signal strength (RSS) can vary with the curvature of the reflector. For example, a convex reflector leads to a drop in the RSS, whereas concave surface increases the RSS. Finally, careful design of the server floor is required to avoid obstacles such as cooling and cable ducts or columns.

B. Pure RF DCNs

In this section, we discuss the designs of pure RF DCNs. There are two main research directions to develop pure RF DCNs, emulation of well-known topologies, and the design of a completely new topology. In the following, we discuss these two research directions.

1) Emulation of Existing Topologies: Vardhan et al. discuss the possibility of realizing a pure 60 GHz DCN [13], [43], [50]–[52]. The authors discuss the emulation of two well-known DCN topologies, 3-tier layered and fat-tree architectures. In order to do that, the authors arrange the servers and switches in racks forming a hexagonal arrangement (see Figure 6) to facilitate direct LOS wireless links. Each rack is equipped with two transceivers mounted to the top of the rack. A transceiver utilize beanforming with phased array to achieve highly directional links. Phase rotator is utilized to steer the beam, and thus communicate with different servers.

In wired hierarchial and Fat-tree DCNs, adding new servers may require rewiring of a large number of existing servers. This can be time-consuming and may affect the availability of the DCN. Vardhan et al., however, present flexible wireless hierarchial and Fat-tree DCNs using 60 GHz technology. Therefore, adding new servers does not interrupt the DCN operation and can be done in a short time. Nevertheless, the work by Vardhan

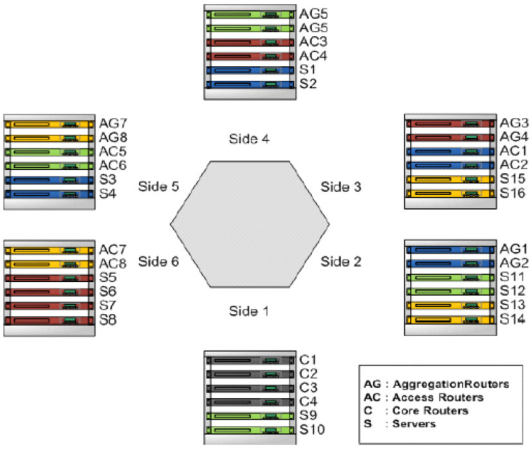


Fig. 6. Design by Vardhan et al. [43].

et al. lacks experimental analysis to fully evaluate the feasibility of the proposed design with respect to link capacities and packet delivery latency.

Influenced by mobile networks [123], we refer to DCN physical topologies that breaks down a network into uniform shapes as cellular DCNs. Foe example, the DCN design proposed by Vardhan et al. can be referred to as a cellular DCN with a single cell. Although modular and can be easily expanded, a cell in cellular DCN topologies encloses unused space leading to DC floor underutilization. Moreover, using a single-cell topology leads to scalability issues.

Flexibility provided by the wireless links can be further utilized to go beyond just emulating the already existing topologies. For example, it can be interesting to investigate the possibility of realizing additional RF on-demand links similar to Flyways [7]. The design by Vardhan et al. can make implementing such links very easy. We believe that this can be an interesting merge that can lead to efficient easy to implement small to medium Fat-tree DCNs.

2) Design of New Physical Topologies: Although Vardhan et al. propose a pure wireless DCN using 60 GHz technology [43], their proposal aims to emulating well-known topologies such as hierarchial and Fat-tree topologies using wireless links. On the other hand, Shin et al. introduce a novel pure wireless DCN design using 60 GHz RF technology [32]. The novelty of the DCN proposed by Shin et al. stems from the fact that the DCN utilizes the properties of the wireless 60 GHz links to realize a physical topology that is different from the standard row-based topology. As a result, the network logical topology is also different from the well-known wired topologies.

The proposed design by Shin et al. features novel cylindrical rack design [see Figure 7]. A rack consists of S stories and each story holds C prism-shaped containers in which servers are stored. Racks are arranged in a semi-regular mesh topology resulting in a densely connected subgraph that is a member of *Cayley Graphs (CG)*. Two wireless transceivers are mounted on both ends of each server node. One is used for intra-rack communication, and the other is used for inter-rack communication. Figures 8-(a) and (b) depict the intra and inter-rack topology in Cayley DCN, respectively. A Y-switch connects the transceivers of a server to its system bus and a routing protocol is used to direct packets within the Y-switch.

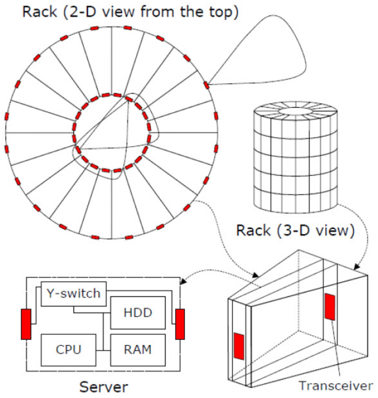


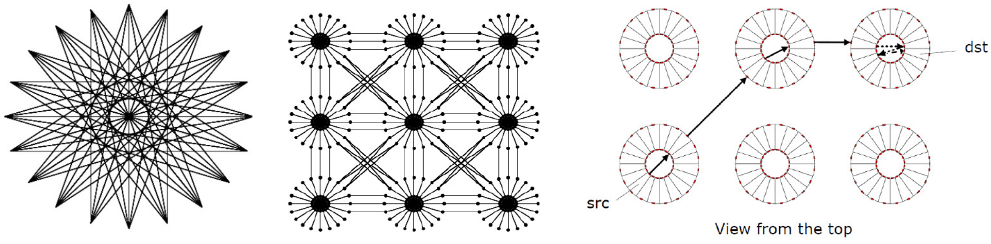
Fig. 7. Rack and server design in Cayley DCN [32].

Figure 8-(c) depicts the diagonal XYZ Routing algorithm used in Cayley DCN. The algorithm is a two-level geographical routing algorithm used to route intra and inter-rack data exploiting the uniform topology of the Cayley DCN. A server is identified by a composition of three values: the coordinates of the rack, the story that contains the server within the rack and the index of the server in the story. A server uses three routing tables to forward package from source to destination using a shortest path route.

A set of experiments is conducted to evaluate the performance (packet delivery latency), failure tolerance, and cost of Cayley DCN. The authors assume a 10×10 grid with $S = 5$ stories and $C = 20$ servers/story. A custom packet level simulator is used to evaluate and measure the average and maximum packet delivery latency of Cayley DCN. Results show that, Cayley DCN exhibits better or comparable performance as compared to Fat-tree DCN, different oversubscription rates. Moreover, Cayley perform better under the assumption that the applications hosted by the DCN generate traffic patterns with small packet numbers and hops. However, this is not always the case in large scale DCNs.

The dense connectivity and the switch-less design leads to high fault tolerance allowing Cayley DCN to withstand up to 59% of node failure before two nodes become disconnected. However, since Cayley DCN relies on multi-hop communication, the maximum latency worsen as the traffic load increases.

In [124], Camelo et al. present a low space and time complexity routing algorithm for any interconnection network where its underlying graph is a CG of some finite group. The proposed algorithm is based on the fact that finite groups are Automatics and have a *Shortlex Automatic Structure (SAS)*. In [125], Camelo et al. extend their work to evaluates the required space to keep such structures and the several intermediate finite state automata that arise during the process of constructing such AS. The authors evaluate six well-known families of CG to determine which structures are space-efficient to implement the scheme based on the so-called *k-fellow traveler* property. Results show that a CG with both low and constant k-fellow traveler property, needs very small routing tables. This was verified in the cases of the CG families Hypercube, Bubble-Sort and Transposition graphs. Other graph families, such as Butterfly and Star, also have a small tables with respect to a general-purpose algorithm for the same kind of graphs.



(a) (b) (c)

Fig. 8. Cayley DC [32] (a) Intra-rack topology. (b) Inter-rack topology. (c) Diagonal XYZ routing.

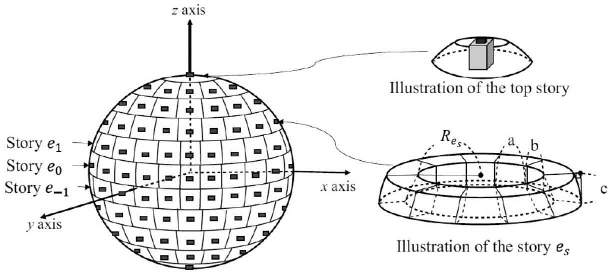


Fig. 9. Design proposed by Suto et al. [126]

However, the reduction of the routing table size only is effective when the number of vertices is very large.

According to Suto et al., Cayley DCN is not fault-tolerant enough to satisfy the requirements of hosting MapReduce. The authors attribute this limitation in Cayley graph to the cylindrical design of the rack. In cylindrical racks, servers are stacked on top of each other forming vertical columns and thus, servers are isolated. This in turn limits the performance of MapReduce. A possible solution to overcome this problem is to increase the degree of all servers in the cylindrical rack. This way, each server can reach more servers in the rack promoting fault tolerance. Nevertheless, this increases interference, and thus reduces spectrum efficiency and increases packet delivery latency.

Therefore, in [126], Suto et al. attempt to design a wireless 60 GHz DCN that satisfies the communication requirements of MapReduce (i.e., better fault-tolerance and better spectrum efficiency). To this end, the authors propose a two-part solution. First, the authors use bimodal degree distribution. This leads to two types of servers, where the majority of servers are non-hub with low degree, and a few become hub servers with higher degree. Hub servers makes the network more fault-tolerant to mechanical faults, whereas using only two types of servers makes the network more fault-tolerant to software faults (e.g., computer viruses).

Hub servers are capable of connecting to multiple servers, however, as pointed out earlier, the cylindrical rack design hinders the connectivity between servers. Therefore, Suto et al. propose a new design of a spherical rack, in which a story forms a disc of servers (see Figure 9). The advantages of the proposed rack architecture are twofold, reduces the hop count for intra-rack communication as compared to that of cylindrical rack and reduces the distance of the intra-rack link, and thus the path power loss.

Results show that as the difference between the transmitter and receiver stories increase, so does the path loss for cylindrical rack design, whereas a spherical rack experiences reduction in path loss. Simulations also show that the spherical rack design leads to lower delivery latency as compared to that of in cylindrical rack in case of hardware faults. On the other hand, the performance of both racks is comparable in case of computer viruses.

It is worth pointing out, however, that the reduction in path loss due to the spherical rack is $<7\%$, whereas, the reduction in data transmission time is $<13\%$. We believe that there are several design complexities associated with the spherical rack design. For example, server containers are not homogenous. This may lead to the management overhead to deal with non-uniform components and parts. Moreover, as we move towards the top, container size decreases. This could be limited by the dimensions of the server contents. It is also not clear how inter-rack communication links will be established or what type of challenges will be faced by racks near the top of the rack. Given that spherical rack leads to limited improvement over the cylindrical rack, extensive analysis and studies are needed to ensure that this is an effective tradeoff.

C. Control Networks and Enabling Technologies

It is worth pointing that the research on wireless DCNs using 60 GHz started to branch out and include techniques adopted from conventional wireless communication systems. Moreover, a few research efforts investigate the use of wireless 60 GHz links to realize control network in DCN [53], [127] instead of using it for data traffic network. In the following we briefly discuss the two topics.

1) Enabling Technologies: In [49], Yamane et al. discuss a method for interference cancelation in distributed MIMO systems. The method is a geometric iterative optimization of signal to interference ratio (SIR) by natural gradients on matrix manifolds. Partial linear zero-forcing is applied to obtain more interference-suppressive initial points that can improve convergence property of the iterative algorithm. Yamane et al. applied their method to a channel model for a typical DC and the simulation results show that this method can improve SIR and achieve higher sum rate at high SNR.

Yu et al. study multicast data delivery problem in [128]. Multicast tree problem is defined, and the objective is to minimize the total multicast data traffic. Yu et al. prove that the problem is NP-hard. An efficient heuristic algorithm is proposed, and results show that the proposed algorithm is effective, compared with an optimal solution designed for traditional wired DCs.

2) Control and Facilities Networks: In [53], Zhu et al. investigate the design of a dedicated facilities network for DCs using wireless communication. A facilities network is a network orthogonal to the data plane and is used to manage DCN. The facilities network is responsible for multiple critical jobs, such as, working as a control plane, and installs and brings up hardware devices.

Control traffic has tighter latency performance requirement as compared to the data traffic which mandates that the facilities plan is isolated from the data plane. Facilities network is different from traditional data plane networks in the sense that it requires lower bandwidth, higher availability, and long-term survivability as compared to those of a data plane. Moreover, the rate at which the bandwidth demands grows is slower.

Zhu et al. propose *Angora*, a low-latency facilities network in which 60 GHz technology with 3D beamforming is used. A testbed used to evaluate Angora, using both experimental measurements and simulations, is developed taking into account link coordination, link interference, and network failures. Results show that Angora can enable large number of concurrent low-latency control channels with high fault-tolerance and flexibility to adapt to workloads and network dynamics.

V. APPROACHES FOR DEPLOYING FSO IN DCNS

Recent research efforts demonstrate the possibility of implementing high capacity indoor FSO links [88]–[90]. In [90], Chowdhury et al. experimentally demonstrate the transmission of a 15 m LOS point-to-point indoor FSO link. The link comprises three channels, uni-directional Cable Television (CATV) signal, and a bi-directional link comprised of two 10 Gbps data links. The authors use LD source that operates in the 1550-nm wavelength range. Direct detection using a PD with active area diameter of 0.5 mm is used at the receiver. To avoid link obstruction due to human movements, the system is placed at a height of 2 m. Results show that the FSO link realized is almost lossless. As expected, for a fixed received power, a better alignment of transmitter and receiver collimators results in more collected and collimated light, and thus received power. This leads to higher SNR and improved bit error rate (BER). The indoor FSO link demonstrated by Chowdhury et al. can be useful for several applications including inter-rack communication in DCNs.

The research on deploying wireless technologies in DCNs is novice, and thus only a few papers [6], [55]–[59], [129]–[131] and patents [132]–[134] discuss the deployment of FSO in DCNs. In the following, we discuss the efforts exerted by researchers to realize hybrid and pure FSO DCNs.

A. Hybrid FSO DCNs

Research efforts on hybrid FSO DCNs can be broken down into two types based on the approach used to configure the links used: mechanically steerable or electronically configurable links. In the following, we discuss both types.

1) Mechanically Steerable Links: In [55], [135], Marraccini and Riza experimentally demonstrate a power smart indoor FSO link that utilizes an electronically controlled variable focus lens (ECVFL). The link is designed to adaptively realize self-imaging effect at the receiver, and thus zero propagation loss via changing the properties of the Gaussian beam propagation. The authors use ABCD matrix analysis of Gaussian beams to theoretically analyze the link performance. A proof-of-concept is realized using an unmodulated 10 mW He-Ne laser operating at 632.8 nm and has a beam divergence of 0.62 mrad. A laser beam profiler is used to receive and measure the signal at different distances from the transmitter (up to 15 m) . Depending on the length of the link, L, the duty cycle of the pulsed wave drive signal is varied to change the focal length of the ECVFL.

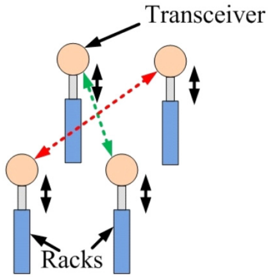


Fig. 10. Design proposed by Riza et al. [55]

Although power smart link should experience zero loss, the non-ideal behavior of the ECVFL and laser beam Gaussian propagation lead to power loss. Moreover, it is not clear whether an attempt has been made to improve the performance of the non-smart link by testing for different specifications for the components used. Nonetheless, results show that the power smart link outperforms non-smart link. For example, at $L = 4\,\text{m}$, the power loss of the power smart link is less than 7%, whereas non-smart link experiences loss of 59.07%. As the length of the link increases, so does the difficulty of obtaining the required focal length for zero loss propagation, and thus both links experience an increasing power loss. At $L = 15\,\text{m}$, the power loss is 92.8% and 61.5% for the non-smart and smart links, respectively.

In [55], Riza and Marraccini discuss different applications in which power smart FSO links can be utilized. One of the applications is inter-rack communications in wireless DCNs. A transceiver is mounted to a pedestal platform that sits on top of each rack. The pedestal allows for vertical and rotational motion such that LOS links between different racks can be established [see Figure 10]. Power smart FSO link can adapt to the varying link length as a rack establishes the links with different racks in the DCN.

Riza and Marraccini focus their discussion on regular indoor, and containerized DCNs in which servers, storage, and networking equipments are placed in a standard shipping ($12.2 \times 2.4 \times 2.6\,\text{m}^3$) containers. Containerized DCNs allow for mobility and modularity, and are easier and cheaper to build. Although highly flexible, mechanical components may significantly add to the complexity and latency of the system. This can increase the risk of failure and affect the availability and durability of DCN components. Moreover, it is easy to keep the length of the FSO links below 15 m in containerized DCNs.

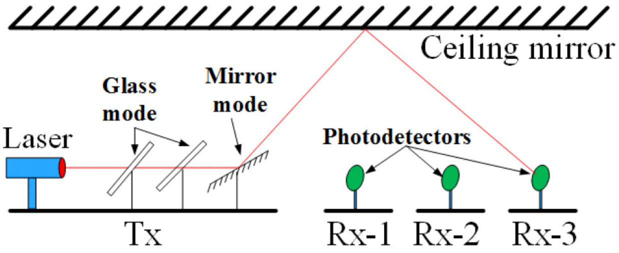


Fig. 11. FireFly by Hamedazimi et al. [6]

However, at the scale of mega DCNs, the effectiveness of power smart links will become less significant.

2) Electronically Configurable Links: Hamedazimi et al. propose *FireFly*, a hybrid FSO DCN [6], [56]. Similar to the 60 GHz RF *Flyways* [44], all inter-rack communications in FireFly are performed using links that are reflected off a reflector (mirror) mounted to the ceil.

In FileFly, FSO transceivers are placed on ToRs. 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 (see Figure 11). SMs are pre-configured and aligned to a receiving FSO on a different rack. According to the states of SMs (i.e., glass/mirror), a link is directed to devices on other racks through the reflection off a mirror mounted to the ceiling. Links are established by switching relevant SMs to mirror/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 beam.

Due to the limited number of FSO modules that can be mounted atop a ToR, a limited number of steering mechanisms (i.e., switchable and Galvo mirrors) must be provisioned and preconfigured so that the network robustness to future and unforeseen traffic patterns is guaranteed. To this end, the problem of designing a FireFly using each of the steering techniques are formulated as a constrained optimization problems. Moreover, the authors discuss different types of real-time reconfigurations required in FireFly, periodic and triggered reconfigurations. The communication and network reconfigurability is controlled using a centralized topology and routing managers. The authors propose a new goodness metric, dynamic bisection bandwidth (DBW), to evaluate the performance of the new flexible network design.

In [136]–[138], we propose a new class of non-blocking multicast FSO switch using non-moveable tri-state switching elements (T-SEs). A T-SE is a switching element that can be reconfigured in one of three states (Fig. 12): *Reflective*, Transmissive, or *Splitting* state (half reflective/half transmissive). Any material similar to the one used in SMs can be used to realize T-SEs. Using the splitting state, a beam can split into any number of copies enabling multicast.

It might be noted that in [6], [56], Hamedazimi et al. use the SMs only in the reflective and transmissive states, and thus links are limited to unicast. Using the design of FireFly and the concept of T-SEs used in our switch to provide multicast, Bao et al. propose FlyCast FSO DCN [59]. In FlyCast, the authors utilize the splitting (referred to as mixed) state of the SMs to enable multicast without the need for a switch. Figure 13 depicts the design of FlyCast. A transmitting rack is preconfigured to communication with three receivers. Reconfiguring the states of the SMs leads to different communication pattern. For example, configuring the first, second, SMs in the glass mode, and third mirror in mirror state will lead to the same link setup in Figure 11. On the other hand, by configuring the first, second, and third mirrors in mixed, glass, and mirror states, respectively, multicast is achieved and the transmitted signal is sent to the first and third receivers.

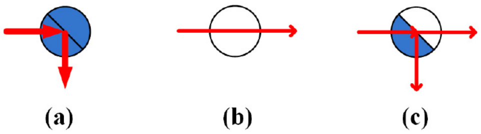


Fig. 12. T-SE (a) R-State. (b) T-State. (c) S-State.

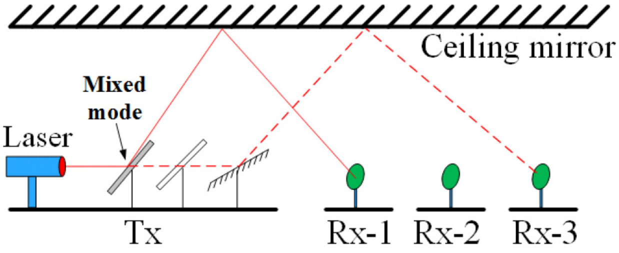
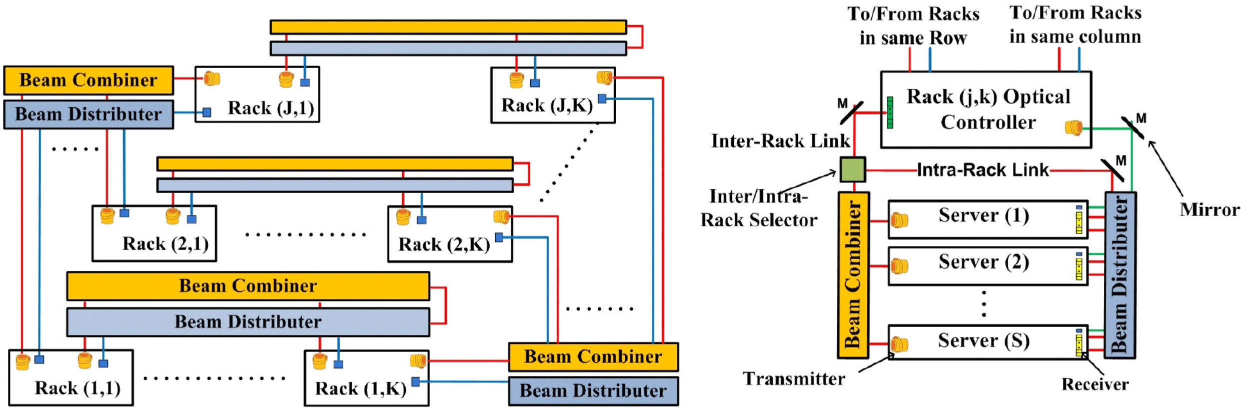


Fig. 13. FlyCast by Bao et al. [59]

Bao et al. use a ring topology to demonstrate the effectiveness of the FlyCast. A signal transmitted by a rack will require multiple hops to reach the destinations. Using FlyCast, a signal can be transmitted simultaneously and in a single hop to the destinations. Similar to FireFly, FlyCast is an SDN. The network controller computes the network topology which reduces to building a directed Steiner tree with constraints. Therefore, computing the topology problem is NP-hard, and thus heuristics are used to implement the control algorithm in the network controller.

In splitting state, light beam is split into two perpendicular beams: transmitted beam (along the path of the original incident beam), and reflected beam. Based on the design, transmitted and reflected beams may or may not have the same power. Bao et al. change the splitting ratio and compute the maximum number of possible signal splitting operations such that the signal remain detectable. The transmittance of the splitter is changed from 10% to 90%. Certainly the maximum number of splitting operations corresponds to the transmittance power of 90%. This is because higher transmitted power can endure larger number of splitting operations. This also matches our results in [57] as we will discuss later. A simple lab experiment is performed to calculate the splitting loss at transmittance of 50%. However, instead of using a SM, the authors use a regular beam splitter with transmittance of 50%.

Similar to the RF *Flyways* [44], the work by Hamedazimi et al. and Bao et al. [6], [56], [59] can provide full flexibility, nevertheless, implementation can be challenging. For example, any imperfection in the ceil mirror can impact the signal reflection leading to signal misalignment. Moreover, obstacles



(a) (b)

Fig. 14. (a) FSO-DC Design. (b) Fully connected switch-free FSO rack.

in the server floor (e.g., building columns and ducts) must be avoided, which may add to the design complexity of the DC. Finally, even though preconfiguration of FSO links are expected to be infrequent, it can be time consuming, require specialized manpower, and it will impact the availability of the DCN.

B. *Pure FSO DCNs*

In [134], Davidson et al. present an extensive theoretical discussion of a pure FSO DCNs. The inventors conceptually discuss connecting DCN components such as: servers, racks, or a set of racks using FSO links, switches, ceiling mirror, mechanically or electrically controllable mirrors and/or beam splitters. However, since the goal of the patent is to cover as much design concepts as possible, the challenges and the details of connecting multiple DCN components using FSO links are not discussed.

Designs of intra and inter-rack FSO links in pure FSO DCNs are independent, and thus it is possible that a designer use preconfigured links for intra-rack, whereas inter-rack links can be mechanically or electronically configurable. Therefore, there is no clear-cut grouping of pure FSO DCNs designs as compared to hybrid DCNs. To improve the readability, however, we divide pure FSO DCN designs into two groups, preconfigured links, and mixed (preconfigured + mechanical steering).

1) Preconfigured Links: In a conventional row-based DCN, we assume that there are $\mathcal{J}$ 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 [see Figure 14-(a)].

To achieve high data rate intra-rack communication, 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 link between all servers. In [57], we propose *FSO-Bus* that can be used to connect any array of adjacent components using point-to-point FSO links.

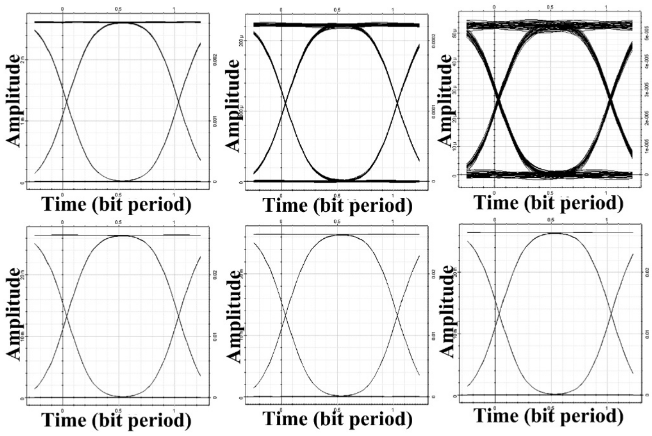
Fig. 14-(b) shows a *switch-free* FSO rack using FSO-Bus. In our design, each server is equipped with an optical transmitter on one side of the server, and an optical receiver comprising a photodetector (PD) [or an array of PDs] on the opposite side. Servers are mounted on the FSO rack such that all transmitters (receivers) of the servers are on the same side of the rack. 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, the beams are directed to the other side of the rack where receivers are placed. Using a beam distributer, beams are 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)*.

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 placed in front of the server to be able to intercept the beams. Each transmitter 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. Several networking and addressing schemes can be used, such as, Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) or Wavelength Division Multiplexing (WDM).

The length of an intra-rack FSO link in the FSO-Bus depends on the source and the destination servers. Therefore, we believe that the FSO-Bus is a good application for the power smart link proposed by Marraccini and Riza in [55], [135]. Moreover, beam splitters can be replaced by the T-SEs discussed in Figure 12. Control signals from the ROC can be used to control the state of the T-SEs depending on the communication pattern. An FSO-Bus using T-SEs will be electronically configurable topology instead of preconfigured.

For inter-rack communication, an *ROC(i,j)* receives data from other racks to deliver to the servers in its rack, communicate with other racks, and relay data received from ROCs in its subnetwork. An ROC is expected to handle large amount of traffic compared to servers, therefore, we envision the use of WDM/DWDM to increase inter-rack link capacities. ROCs in the same row/column of racks can be connected using the FSO-Bus.

In our design, servers and racks are connected using point-to-point, NLOS links formed using specular reflections (i.e., a set of mirrors and beam splitters). Therefore, efficiencies and



(a) (b) (c)

Fig. 15. Eye Diagrams of FSO (top) and Fiber Optics (bottom) at 2.5 Gbps and $P_T = 10\,\text{mW}$ (a) s = 1. (b) s = 25. (c) s = 39.

power reductions caused by mirrors and beam splitters must be incorporated in the power budget analysis [57]. These losses and factors depend on the number and arrangement of mirrors and beam splitters in the design.

We use OptiSystem software to evaluate the performance of the FSO-Bus. We assume that the number of servers in a rack is $S = 40$. Optical efficiency of all transmitters/receivers optics, mirrors and BSs are assumed to be 99%. The power of the reflected light beam by a splitter is 10%, and thus the transmitted power is 90%. An FSO link is implemented with an FSO channel of five meters and wavelength of 1500 nm. For the sake of comparison, we also implement a fiber optic link with similar characteristics. Both transmitters use OOK NRZ modulation scheme.

Figure 15 depicts the eye diagrams of the FSO and fiber optical links at 2.5 Gbps received by the servers 1, 25 and 39. As we move towards the bottom of the rack, the power received decreases, degrading the performance of the FSO link. On the other hand, it is difficult to notice any variation in the fiber optical link since the link is too short, and the received power is not affected by BSs or mirrors as in the FSO link.

Results confirm that FSO-Bus is feasible for intra-rack communication. However, long distances are involved in in case of inter-rack communication. Therefore, Gaussian beam divergence can make inter-rack communication using FSO-Bus challenging. Moreover, it can be argued that large number of discrete optical components is needed to realize FSO-Bus.

In [58], Arnon discusses both, intra-rack and inter-rack communications using FSO. For intra-rack communication, server should be able to communicate with each other and with the ToR using inter-server OWC transceivers. However, the structure the inter-server OWC transceiver and the means of establishing FSO links between servers are not discussed.

In the case of inter-rack communication, racks are arranged in circular cells such that neighboring racks can communicate using LOS OWC links. Moreover, ToRs within a cell can communicate with Aggregate (or core) switches located at a higher layer as shown in Figure 16. 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 design has not been addressed, and thus, it is not clear how racks, aggregate, and core switches, are connected on a large scale. Similar to the work by Vardhan et al. [43], cellular DCNs can lead to DC space underutilization.

2) Mixed (Preconfigured + Mechanical Steering): A bi-directional point-to-point FSO link design utilizing high power, high speed vertical-cavity surface-emitting laser (VCSEL) arrays is presented by Joseph et al. [133]. The inventors discuss communication inside DCNs (i.e., inter/intra-rack) as one of the applications of their invention. They envision intra-rack communication to be performed using a ToR optical switch employing a multiple lens array. Servers in the rack send information to the ToR Switch as shown in Figure 17-(a). The optical switch then directs the information back to the servers using data shower beams. The switch can be placed at the top, bottom, or middle of the rack cabinet.

In the design proposed by Joseph et. al. [133], the optical switch must be equipped with number of transceivers equal to the number of servers. For large number of servers, this design may become intractable or expensive. Moreover, an intensive alignment effort is needed to adjust each beam to hit the corresponding lens in the multiple lens array mounted to the lower surface of the switch.

For the inter-rack communications, optical switches or transceivers are mounted to a polygonal structure. For example, Figure 17-(b) depicts six switches (transceivers) mounted to a hexagonal structure. Similar to the work by Marraccini and Riza [55], [135], the structure is mounted to a pedestal system that allows rotational and vertical height adjustments. This arrangement can be very useful for cellular FSO DCNs.

We chronologically summarize the main studies in the area of wireless DCNs in Table III. We list the highlights, physical and logical topologies of the DCN, and whether simulations are performed to evaluate the proposed designs. We also list the main drawback of each proposed design which we discuss in detail in the following section.

It is worth pointing out, however, that the reduction in path loss due to the spherical rack is $<7\%$, whereas, the reduction in data transmission time is $<13\%$. We believe that there are several design complexities associated with the spherical rack design. For example, server containers are not homogenous. This may lead to the management overhead to deal with non-uniform components and parts. Moreover, as we move towards the top, container size decreases. This could be limited by the dimensions of the server contents. It is also not clear how inter-rack communication links will be established or what type of challenges will be faced by racks near the top of the rack. Given that spherical rack leads to limited improvement over the cylindrical rack, extensive analysis and studies are needed to ensure that this is an effective tradeoff.

VI. WIRELESS DCNs: CHALLENGES AND LESSONS

Applications hosted by DCNs (e.g., Hadoop and Spark) generate large demands for intra and inter-rack communication bandwidth. To meet such demands, new communication technologies must be capable of achieving high link and network

TABLE III

SUMMARY OF MAJOR WIRELESS DCN RESEARCH DIRECTIONS.

Wireless Technology	Highlights	Reference	Year	Simulation	Physical Topology	Logical Topology	Challenges
RF	First proposal of a wireless DCN in general, and using 60 GHz RF links in particular.	Ramachandran et al. [42]	2008	✗	NA	NA	NA
Hybrid RF	Motivate using Flyways, on-demand additional links (wired or wireless), added to provide additional capacity.	Kandula et al. [7]	2009	✓	Rows	Tree	• Topology-independent model (a module can communicate with any module within its range.) • Non-configurable links with fixed capacity.
Pure RF	A preliminary study to propose the idea of emulation well-known existing topologies, such as Tree and Fat-tree using pure 60 GHz DCNs.	Vardhan et al. [43]	2010	✗	Cellular (hexagonal single cell)	Tree/Fat-tree	Limited scalability as a complete DCN is designed using a single hexagonal cell of racks.
Hybrid RF	Performance measurement and simulations are done using 60 GHz devices prototype to evaluate the viability of flyways [7] concept.	Halperin et al. [44]	2011	✓	Rows	Tree	• Topology-independent model (a module can communicate with any module within its range.) • Non-configurable links with fixed capacity.
Hybrid RF	Addressing the design of a hybrid network architecture and formulating the provisioning of links in a hybrid RF DC into an optimization problem.	Cui et al. [17], [45], [46]	2011	✗	NA	NA	Topology-independent model (a WTU can communicate with any WTU in its range).
Hybrid RF	Guaranteed LOS links between adjacent rows of racks. Data is relayed row by row.	Katayama et al. [47]	2011	✗	Rows	NA	Poor performance with respect to packet delivery latency is expected due to the multihop communication.
FSO	• Propose power smart indoor FSO link using electronically controlled variable focus lens (ECVFL). • Suggest the use of power smart links in DCNs.	Marraccini and Riza [135]	2011	✗	NA	NA	NA
Hybrid RF	Propose and realize 3D beamforming 60 GHz links reflected off the ceil to overcome the LOS problem.	Zhang et al. [48]	2011	✗	Rows	Flexible	• Complexity of establishing a link. • Effect of ceil reflector's imperfection.
Hybrid RF	Extend their work by establishing a small 3D beamforming testbed to evaluate the work in [48].	Zhou et al. [18]	2012	✗	Rows	Flexible	
Pure RF	Pure 60 GHz DCN that features cylindrical racks arranged in semi-regular mesh and connected by a special Cayley Graph.	Shin et al. [32]	2012	✗	Cellular	Cayley	Cellular topology may lead to higher packet delivery latency due to multihop communication.
Hybrid FSO	Extend their work in [135] by discussing applications of power smart links and suggest the use of mechanical pedestals to establish LOS inter-rack links.	Riza and Marraccini [55]	2012	✗	Grid	NA	Mechanical systems present a risk of failure that may impact the availability and durability of the network.
Hybrid FSO	• FSO links are configured using switchable mirrors and ceil mirror. • A configurable link is realized by choosing from a set of preconfigured links.	Hamedazimi et al. [6]	2013	✓	Rows	Flexible	• Imperfection of the ceil mirror. • Manual preconfiguration can be time consuming, require specialized manpower, and impact the DCN availability.
Pure RF	Theoretically analyze the viability of their proposed work in [43]. Prove that a Fat-tree DCN can be represented using a pentagonal shaped cell of racks.	Vardhan et al. [13]	2013	✗	Cellular (hexagonal single cell)	Fat-tree	Limited scalability as a complete DCN is designed using a single hexagonal cell of racks.
. Pure FSO	• 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. [57]	2014	✗	Rows	Crossbar	FSO-Bus design depends on discrete optical components.
Hybrid FSO	Extend their work [6]. Links can be configured using switchable mirrors or Galvo mirrors.	Hamedazimi et al. [56]	2014	✓	Rows	Flexible	• Imperfection of the ceil mirror. • Manual preconfiguration can be time consuming, require specialized manpower, and impact the DCN availability.
Pure RF	• Extend their work in [13], [43] and divide Fat-tree network components (servers and switches) into spatial clusters and arrange them in a single hexagonal cluster. Use TDMA to increase the transmission concurrency and reducing or eliminating interference. • Formally define their work in [13], [43], [51] as Polycell, a wireless DCN.	Vardhan et al. [50]–[52]	2014	✗	Cellular (hexagonal single cell)	Fat-tree	Limited scalability as a complete DCN is designed using a single hexagonal cell of racks.
Pure FSO	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 [58]	2015	✗	Cellular	NA	Cellular topology may lead to higher packet delivery latency due to multihop communication.
Hybrid FSO	Extends the work in [6], [56] by utilizing a third state of the switchable mirrors to allow physical layer multicast eliminating the need for switches.	Bao et al. [59]	2015	✗	Rows	Flexible	• Imperfection of the ceil mirror. • Manual preconfiguration can be time consuming, require specialized manpower, and impact the DCN availability.
Pure RF	• Use bimodal degree distribution to improve fault tolerance. • Propose a spherical rack design to improve intra-rack connectivity.	Suto et al. [126]	2015	✓	NA	NA	• Server containers in the spherical rack are not homogenous and reduce in size at higher stories. • Limited improvement over the cylindrical rack.

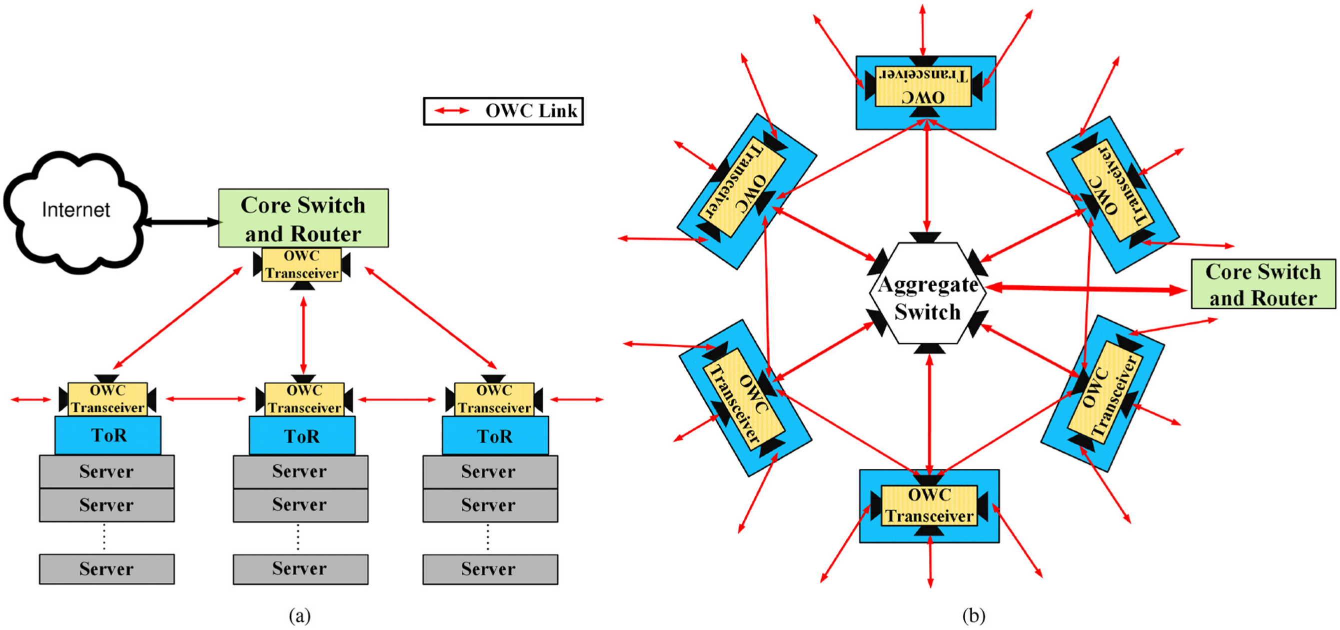


Fig. 16. Design proposed by Arnon [58] (a) Side view. (b) Top view.

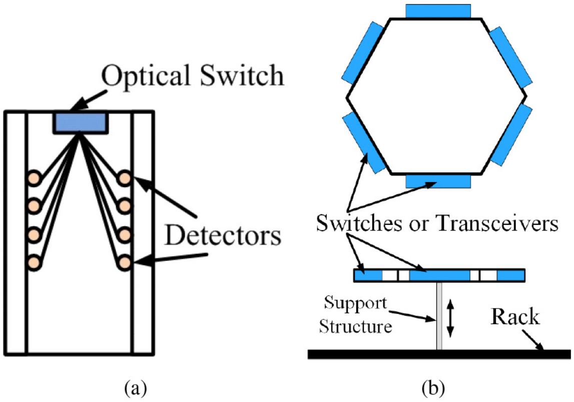


Fig. 17. Design proposed by Joseph et al. [133] (a) Intra-rack. (b) Inter-rack top (top) and side (bottom) views.

capacities. However, realizing high-bandwidth links can be challenging, and these challenges vary depending on the technology used for communication. In this section, we discuss the challenges facing the deployment of wireless technologies in DCNs and the lessons learned from the literature. We start by discussing the challenges that may face any wireless technology to be deployed in DCNs, then we focus our discussion on technology-specific challenges:

1) Security: In a DCN, often data is exchanged between nodes in different racks to complete tasks. Therefore, isolation of data from unintended nodes and services is a must to avoid security and privacy problems.

The limited transmission range of 60 GHz and the inability to penetrate obstacles prevent 60 GHz signals from traveling further than their intended target. Moreover, the use of narrow beam width makes it easier to target only the intended receiver. This makes 60 GHz technology immune to eavesdropping. On the other hand, one of the distinct advantages of FSO technology is its inherent PHY layer immunity to eavesdropping as compared to most RF technologies. Wireless DCN designers must take advantage of this feature and develop efficient low-overhead security protocols at higher networking layers. This means that less overhead, and more useful data can be transmitted leading to higher throughput and improved overall performance.

2) 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 [129]. 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.

3) Heat and Air Flow: DCN designers may change the rack arrangement in DCN floor (i.e., physical topology) instead of using the conventional row-based arrangement to fully utilize the flexibility provided by wireless links (e.g., cellular DCN design). Any change in the DCN floor, however, can cause changes in the air flow and heat distribution properties. This may in turn lead to inefficient cooling, and thus network component failure or higher power consumption. Moreover, it can also cause turbulence and may impact the performance of FSO links. 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 DCN.

4) Agile Links: To address the hotspot problem encountered by wired DCNs, inter-rack wireless links must have a degree of reconfigurability. One of the main challenges faced by wireless DCN designers is establishing and maintaining wireless links between different servers or racks. There are several methods that can be used to realize agile links. Some of them work for both, RF and FSO, technologies, whereas other methods could be technology-specific.

- Mechanical steering. The main idea is to steer RF horn antenna or FSO transceiver. mounted to pedestals that sit on top of rack cabinets. Both rotation and height of the transceiver can be controlled allowing for establishing flexible wireless links [55], [135], [133].

As discussed earlier, mechanical components can add to the complexity and latency of the system, and can increase the risk of failure. These limitations can be addressed using the following technology-specific solutions:

- RF Beamforming using phased array antennas can provide very fast steering, however experiences signal leakage, and thus weaker signals.
- FSO Preconfigurable-Electronically Reconfigurable Links. In this type of links, a link is electronically reconfigured to choose from preconfigured link configuration [6], [56], [59]. There is no guarantee, however, that the preconfigured links are efficient. Moreover, manual change of the preconfiguration is needed.

There is a need for new means for realizing agile wireless links in RF and FSO DCNs.

5) Obstruction-Free Wireless Links: At the scale of mega DCNs, hundreds of racks must be interconnected, and thus wireless DCN should scale to meet this large link connectivity requirements. Network resources must be efficiently provisioned to meet the requirements of hosted DC services and applications, and to maintain a minimum level of availability. However, a critical impediment to the design of wireless DCN is the difficulty establishing *obstruction-free* wireless links to connect multiple adjacent network components. 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 [57]. Several solutions appear in the literature to overcome this problem. Different solutions present different tradeoffs with respect to simplicity and configurability. In the following, we discuss these solutions:

- Configurable Link + Ceil Reflector: this solution is proposed in both 60 GHz, and FSO DCN literature. In this design a configurable link is used to transmit the signal towards a reflector (e.g., mirror in case of FSO). The signal reflects off of the reflector towards the destination node. The configurable link can be obtained using any of the techniques discussed in "Agile Links". This solution can provide obstruction-free links covering most of the DCN. However, alignment and configuration of the link can be complex. Moreover, it depends on the degree of reconfigurability of the transmitter.
- Cellular (circular, polygonal, or spherical) Design: although can provide limited configurability, cellular design guarantees simple LOS wireless links. In case of cellular design, wireless transceivers can be placed on ToRs at a height that is above the average human height, so human movements do not obstruct the link [89], [90]. Cellular designs, however, usually involve unutilized space enclosed by the cells.

6) Containerized DCNs: Many existing and under development DCs utilize large open DCN floor design. However, as discussed in Section V-A, containerized DCNs can present a cheaper and an efficient alternative design. A few papers discuss the deployment of 60 GHz RF and FSO technologies in the containerized DCN scenario [44], [55]. As a container becomes the building block of a DCN, intra and inter-container communication links must be designed.

At the scale of a container, problems related to cabling complexity may not be significant. Moreover, using wireless communication to replace the wiring infrastructure in a DCN container may help increase the number of servers by only a few. Therefore, studies are needed to ensure the viability of wireless technologies deployment in DCN containers.

Once proven viable, other technical issues must be taken into consideration during the deployment of wireless communication in DCN containers. Confined space and metal walls make the container a challenging environment for 60 GHz links as signals may reflect off the walls leading to multipath fading. A possible solution to alleviate the multipath fading in containers is to cover the inner of the container with adsorbent materials, or by employing very narrow beam antennas [44]. On the other hand, environmentally controlled containers are very suitable for FSO communication.

Inter-container links carry the traffic of the container, and thus must provide higher bandwidth. However, 60 GHz can be of limited capacity with respect to the container traffic. On the other hand, FSO can provide the required capacity, however, it becomes prone to the environment impairments and techniques used for outdoor FSO links must be applied to mitigate such impairments. It is possible that multiple links and MIMO techniques can be used to provide the required inter-container traffic.

In addition to the challenges and requirements discussed above, each technology can experience unique technology-specific challenges and requirements. In the following we discuss the challenges specific to 60 GHz RF, and FSO technologies.

A. Challenges for 60 GHz in DCNs

1) 60 GHz Behavior Modeling and Analysis: In [54], Zaaimia et al. present initial measurements of 60 GHz RF channels in a real campus DCN. Authors perform experiments on two inter-rack measurement sets, cross aisle (racks from parallel rows) scenario set, and neighbor (on the same row) racks scenario set. Channel transfer function is measured using a channel sounder that is based on vector network analyzer. In order to verify the accuracy of measurements, the authors conduct ray tracing simulations as well. Needless to say, neighbor racks scenario show a 3 dB improvement in the link budget over cross aisle scenario.

The research on wireless DCNs is relatively novice. Therefore, large number of new unprecedented design concepts and topologies are emerging. All designs aim to fully utilize the flexibility presented by 60 GHz technology. A major conclusion from the study by Zaaimia et al. is that path loss of 60 GHz link is environment-dependent. Therefore, there is a current need for an accurate modeling scheme of wireless DCN environment. This can be a challenging task due to the high density of metal structure in DC. Moreover, having a design or simulation tool can be of great interest to DCN designers to test the physical topology of their DCNs.

2) RF Channel Allocation and Frequency Reuse: Channel allocation can be classified as fixed (FCA), dynamic (DCA), and hybrid (HCA). In FCA schemes, a channel or set of channels is permanently allocated to each RTU. In DCA, all channels are kept in a central pool and are assigned dynamically to new links. This assignment can be done by a central controller or the allocation scheme can be distributed. HCA is a combination combination of both FCA and DCA techniques. in HCA, the total number of channels available for service is divided into fixed and dynamic sets. Fixed set is assigned to RTUs, whereas the dynamic set is shared by all DCA.

In DCs, the decision of which channel allocation scheme to use mainly depends on the type of DCN. For example, in case of hybrid DCNs, wireless links are used to provide on-demand links to enhance the performance. Therefore, FCA is not a good choice as it will lead to channel underutilization due to the unused assigned channels, and DCA in this case is more suitable.

On the other hand, in case of pure DCN, performing scheduling every time a server sends a signal is not practical. Moreover, the traffic patterns can lead to unfairness as few servers can dominate the links. Therefore, using DCA in a pure DCN can be inefficient. However, given the scale of DCNs and the large number of nodes and the limited number of channels, FCA in pure RF DCNs requires careful assignment and scheduling to reduce the impact of interference.

60 GHz technology has lower link range and very limited ability to penetrate obstacles. This in turn promotes frequency reuse. However, the frequency reuse in DCNs is not yet explored. We envision that wireless DCNs can benefit from the mature mobile network systems. For example, a DCN plane can be divided into logical cells. Each cell can be assigned a set of frequencies, such that the frequencies are used across the DCN. This way the channel allocation problem becomes at the scale of a cell, and thus simpler than the channel allocation and scheduling at the DCN scale. This will also lead to a faster allocation using developed heuristics or using any of the well-known evolutionary algorithms, such as Genetic Algorithm (GA) [139], Particle Swarm Optimization (PSO) [123], or Binary Harmony Search Algorithm (BHSA) [140].

B. Challenges for FSO in DCNs

1) Visible vs. Infrared Sources: The experiment by Chowdhury et al. [89], [90] has shed some light on the potentials, as well as limitations, of FSO links for DCNs. Although FSO links are capable of providing lossless high data rate transmission, point-to-point FSO links require careful installation and alignment [89], [90]. Using visible light sources can ease the alignment of FSO links in FSO DCNs. However, most off-the-shelf components such as 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. Therefore, there is a current need for the development of communication components (e.g., high speed optical modulators) required for establishing high data rate point-to-point FSO links using LDs operating in the visible region of the spectrum.

2) Artificial Light Sources: In the absence of the background radiation, ambient artificial light becomes the dominant source of noise for indoor FSO systems [57]. 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 [70], [141]. 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 DCNs is to illuminate the DC using LED sources that are out of band with respect to the LDs used for communication [57].

3) 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 can lead to link misalignment [142], and thus add to the complexity of the FSO link design. There are three possible solutions for the vibration problem:

- Use active vibration isolation (AVI) system [102]. Although this is suitable for lab experiments, in case of large number of links such as in DCNs, this solution can be expensive.
- Increase the width of the beam such that it overfills the detector at the receiver side allowing for vibration tolerance. In case of minor misalignment due to vibration, the receiver will still be able to receive sufficient power to maintain the link. According to Hamedazimi et al. [56], 6 mm vibration tolerance is sufficient to handle minor misalignment due to vibration. This solution, however, requires the use of detectors with higher sensitivity, and thus more expensive transceivers must be used.
- Mount optical transceivers 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. This solution can't completely alleviate the impact of vibrations. Moreover, the metal frames can lead to underutilization of the DC space.

VII. FUTURE RESEARCH DIRECTIONS IN WIRELESS DCNS

The incorporation of wireless communication technologies in DCNs is still in its infancy, thus, it still needs great investigation and development in order to become an efficient practical reality. Some interesting design considerations and open questions involve [32]

Hybrid versus Pure DCNs. As we mentioned before, wireless links can be used to augment existing wired DCNs or to realize a pure wireless DCN. However, it is not yet clear which type of DCNs can provide a more efficient solution. Pure wireless DCNs are envisioned to solve cabling complexity and hot spot problems. However, it is possible that some degree of wired connectivity for intra/inter-rack communication can benefit the performance [32]. In order to answer this question, all possible solutions on the DCN design space including pure wired DCNs, hybrid DCNs, and pure wireless DCNs must be explored. Large number of possible DCN realizations fall under the umbrella of hybrid DCNs. Thus, it is important to find the optimum combination of wired and wireless networks to realize an efficient DCN.

Goodness Metrics. The bisection bandwidth and diameter metrics used commonly to model the static prospective of the topology which is suitable for wired DCNs [6], [56]. To characterize the flexible and dynamic network topology a flexible wireless DCN can provide, a notion of dynamic bisection bandwidth or at least a lower (upper) bounds is needed [6], [56].

Network Architecture. While it is intuitive to replace wired links by wireless links using the same DCN arrangement, we believe that the flexibility provided by wireless links can not be fully exploited unless new topologies and DCN arrangements are used. A network architecture must address the requirements of future DCNs, including scalability, high capacity, and fault tolerance. Characteristics of 60 GHz and FSO technologies, such as, the short transmission range, necessity of LOS, and the interference among 60 GHz wireless links must be taken into consideration [53], [143].

Cost Tradeoffs. In pure wireless DCN, switching and communication functionalities are shifted from few powerful, high-power, and high-cost nodes (switches, and routers) to a large number of low-power and low-cost end points (i.e., servers). It is crucial to understand the cost structure of individual nodes to decide whether one or a combination of these design possibilities will lead to an efficient cost-effective DCN [32].

Visible Light Communication (VLC). VLC is another rapidly emerging technology in which light emitting diodes (LEDs) are used to provide VLC data links as well as illumination. We envision that, not only LEDs can be used for illumination in DCNs, but also it can be utilized for communication and networking (e.g., unicast/broadcast of control signals).

Hybrid Wireless DCNs. FSO and 60 GHz technologies have different attributes, advantages and disadvantages. Moreover, FSO does not interfere with RF spectrum [57]. This makes the OW a good candidate for applications in which mitigating interference with RF systems is a must, such as in personal entertainment systems on commercial aircrafts and in hospitals [57], [95]. Therefore, research community considers RF and FSO as two complementary technologies that can jointly provide a broad spectrum of capabilities (e.g., 5G) [57].

We envision that the integration of both wireless communication technologies (i.e., RF and FSO) in DCNs to realize a *hybrid wireless DCN* is a promising research direction. It is, however, challenging to envision a hybrid wireless DCN. This is because current research has not yet explored all the potentials and challenges of deploying wireless communication in DCNs. In order to realize the best possible designs, we must first develop the best practices in wireless DCNs.

One approach to develop hybrid wireless DCN may be based on small clusters of RF operated racks. In each cluster the set of all available frequency channels is used. This prevents the intra-cluster interference problem. The DCN might be organized such that the clusters are distant enough to prevent inter-cluster interference. This is doable since the 60 GHz technology has a limited short range. Moreover, additional FSO links can be used safely for intra-cluster communication since FSO does not interfere with the RF. On the other hand, for inter-cluster communication, FSO LOS links can be used. This concept is analogous to the *coverage cells* in mobile communication, except that there is no mobility or handover needed.

VIII. SUMMARY

DCs have become a critical part of today's computing and enterprise infrastructures. Currently deployed wired DCs suffer from increasing cabling complexity and hotspots problems. This has motivated the researchers to investigate the possibility of incorporating wireless technologies into DCs. Existing surveys and classifications on DCs chiefly focus on wired DCs. In this paper, we present a detailed survey on wireless DCs.

We start by comparing the two potential candidate technologies for wireless communication in DCs, namely; 60 GHz and FSO. Comparison shows that both technologies are unlicensed and have link length suitable for the confined environment of DCs. Moreover, 60 GHz and FSO technologies depend on LOS links, but 60 GHz technology has lower practical bandwidth and can be affected by interference. On the other hand, FSO links require careful alignment to maintain the LOS.

We propose a classification that can be used to classify any DC, including existing wired and emerging wireless DCs. Our classification is based on the communication technologies used to realize the DCN. According to the proposed classification, wired DCs can be classified as pure electrical/optical wired DC, or hybrid wired DC. On the other hand, wireless technology can be used either to augment wired DCs resulting in hybrid DCs, or to realize pure RF/FSO DC. We discuss different wireless-based DC designs and collate the major work in the field to jump-start researchers to tap into the growing research on wireless DCs.

Several research questions and design challenges must be investigated before wireless DCs can be realized. Based on the classification and the review of existing literature, we believe that the following two questions are the key research questions;

- Can a wireless technology alone satisfy the requirements of future DCs in a pure wireless DC fashion, or do we need hybrid DCs?
- Given a wireless technology, what is the best network architecture and topology?

Using the proposed classification, we now have a nearly complete picture for the design space of DCNs. By surveying the literature and mapping existing solutions to different possible designs in the proposed classification, it is now possible to easily identify new research areas. For example, in this paper, we were able to identify that the area of hybrid wireless DCNs has not yet been explored.

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