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Survey paper

60 GHz wireless data center networks: A survey

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ABSTRACT

Data centers (DCs) became an important part of computing today. A lot of services in Internet are run on DCs. Meanwhile a lot of research is done to tackle the challenges of high-performance and energy-efficient data center networking (DCN). Hot node congestion, cabling complexity/cost, and cooling cost are some of the important issues about data centers that need further investigation. Static and rigid topology in wired DCNs is an other issue that hinders flexibility. Use of wireless links for DCNs to eliminate these disadvantages is proposed and is an important research topic. In this paper, we review research studies in literature about the design of radio frequency (RF) based wireless data center networks. RF wireless DCNs can be grouped into two as hybrid (wireless and wired) and completely wireless data centers. We investigate both. We also compare wireless DCN solutions in the literature with respect to various aspects. Open areas and research ideas are also discussed.

1. Introduction

Cloud computing is becoming more and more popular every day. It provides remote access to computing and storage resources and is used for wide range of applications run by small or big corporations like Google and Microsoft. Cloud computing services can be divided into three basic categories depending on the service type: (i) Software as a Service (SaaS), e.g., Gmail, Facebook; (ii) Platform as a Service (PaaS), e.g., Google App Engine [1], Microsoft Azure [2]; (iii) Infrastructure as a Service (IaaS), e.g., Amazon EC2 [3], Sun Cloud Storage Services [4].

Data centers (DCs), which are the core infrastructures of cloud computing, are composed of large number of nodes, servers and switches, that are connected with each other for distributed computing, storage, or providing services. Only Google had around 900,000 servers in year 2010 [5] and now has millions of servers worldwide. DCs are mostly hosted by large companies like Google, Microsoft, Amazon, and Dropbox, for both customer-use and internal-use. However, small companies also set up small-scale data centers for their customers. As cloud computing evolves, the need for DCs and the size of them are increasing as well. [6] states that the growth in number of servers in data centers is exponential.

[7] points out that the primary bottleneck in data center networks (DCNs) is inter-node communication, i.e., links between servers in a DC. According to a white-paper of Cisco [8], 77% of a data center traffic is forecasted to be "within data center" in year 2020. This traffic is composed of storage, production/development data, and authentication.

Due to the high rates of intra-data center traffic, links and topologies used inside data centers should ensure high end-to-end bandwidth. Therefore, it is important to design efficient network architectures and topologies. Portland [9], BCube [10], and VL2 [11] are some examples of efficient wired network topologies and protocols proposed for DCNs.

Common data center connection topologies are tree structured. There are usually two tiers of switches, namely, core and aggregation switches, at the top two levels of the tree, and servers are placed in racks at the lowest level. At the top of each rack, there is a top-of-the-rack (ToR) switch connected to an aggregation switch. It is usually the case that the core layer is the most utilized layer [12]. This design does not provide direct communication between servers placed in different racks. Those servers can connect to each other using aggregation and core switches. If not needed, core switches may not be used for close-rack communications. For example, for the interconnection of servers residing in the same rack, just the top-of-the-rack (ToR) switches can be used. Since the same-rack servers are connected directly to their ToR switch, the traffic between them do not need to circulate the whole network. As the network grows, the number of switches and the amount of cabling increase, and the network becomes more complex.

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Depending on the distributed applications running on a DC, some nodes (some servers or switches) may send and receive more traffic than the others, and this may cause an *oversubscription* on some of the links when the potential traffic demand exceeds the capacity of the links. As mentioned earlier, there are various wired-topology based solutions to this problem, and they require large number of switches, routers [13] and redundant physical links. Therefore building such wired topologies is expensive [14,15]. [16] states that data center solutions like Fat-tree [7] and VL2 [11] are three or four times costlier than the traditional tree topology.

Although DCNs are well-studied over the past ten years, there are still open problems and challenges in this area. Some of these problems can be listed as follows:

- Hot node congestion: some nodes need to send and receive much more traffic than the others;
- Static structure, i.e., not configurable: wired topology is rigid and cannot be changed easily and frequently, cabling is complex;
- Costly: switching cost due switch prices, cabling cost, energy and cooling.

It is realized that these problems can be partially or fully solved using wireless communication in DCNs. Hot node congestion can be solved by flexibly assigning direct wireless links between frequently communicating nodes. Traditional DCs cannot efficiently deal with random hotspot problem due to their static and rigid topology. Switching costs can be decreased by bypassing wired paths going over a lot of switches via wireless links. Cooling cost can be decreased by reducing the number of cables that affects ventilation [17].

As investigated in [18], cabling cost and complexity can be decreased by using wireless links. Wired links between distant racks can be replaced with wireless links to simplify network structure and to reduce the amount of cabling. However, an issue that needs to be considered is the energy consumption due to use of wireless transceivers. Wireless transceivers should not bring a very big overhead in terms of energy compared to wired switches. It is stated in [6] that the maximum power consumption of a 60 GHz transceiver is around 0.3 Watt, which means that such transceivers can easily be favored in a data center with tens of thousands of servers.

In this paper, we survey and compare the studies that propose the use of wireless links in data centers to overcome the aforementioned problems. We investigate the studies in two categories: (1) the ones that use wireless links together with wired links (hybrid data centers — HDCs), (2) the ones that use just wireless links to build data center networks (completely wireless data centers — CWDCs).

The rest of the paper is organized as follows. In Section 2, we present information about some possible wireless technologies, particularly 60 GHz technologies, that can be used for data center networking. In Section 3 we present and discuss various studies on wireless data center networks. In Section 4 we summarize the studies and provide our conclusions.

2. 60 GHz wireless

Wireless technologies used for data center networks can be divided into two categories as (1) radio frequency (RF) based technologies and (2) free space optics (FSO) based technologies, as mentioned in Hamza et al. [19]. RF wireless uses radio waves as in Wi-Fi, however, FSO uses light beams (optical). FSO is a wireless optical communication technology. It uses light to transmit information wirelessly in a free space (like air) in high data rates requiring line-of-sight alignment. In this paper we will only focus on RF based wireless data center networks by examining the studies in this area deeper. Therefore, "wireless data center technology" term used in this work refers only to RF.

Since wireless communication can bring lots of benefits to DCNs, appropriate wireless technologies should be used to satisfy the needs of DCs. DC applications are data-centric, therefore the selected wireless technology must support high data rates. Data rates supported should be at least 1 Gbps. 2.4 GHz WiFi standard, which is operating in an unlicensed ISM band, is widely used in home and office networks and also in industry. It supports communication range of 100 m and does not need line-of-sight alignment. Maximum data rate is 866.7 Mbps in typical off-the-shelf devices, although it can reach to speeds as much as 6.9 Gbps in special installations [20]. The channel bandwidth is 22 MHz and there are multiple channels that can be used. Three of these channels are orthogonal. Although being an option, 2.4 GHz WiFi is not very suited to completely replace wired links and carry the huge amount of traffic that needs to be transported in a datacenter every second.

Table 1
802.11ad frequencies in different regions.

Region	Frequency range (GHz)	No of channels
Europe	57.00–66.00	4
United States	57.05–64.00	3
China	59.00–64.00	2
Australia	59.40–62.90	2

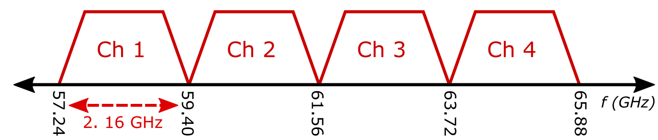

Fig. 1. Characteristics of 802.11ad channels.

Another unlicensed wireless band resides at around 60 GHz in electromagnetic spectrum [21] (57–64 GHz in US). It is part of the extremely high frequency (EHF) RF band (30 to 300 GHz). Due to its 5 mm wavelength, $\lambda = c/(6\times10^7$ Hz), it is also called as millimeter wave. We will use the terms 60-GHz and millimeter-wave interchangeably in this paper. The spectrum used in 60 GHz communication is wider than Wi-Fi, and therefore provides higher bandwidth. There are already wireless communication standards developed that use millimeter wave communication: 802.11ad [22,23], 802.15.3c [24], WirelessHD [25], and ECMA-387 [26].

Although 802.15.3c standard is the subject of some papers like [27], most of the studies in literature are based on 802.11ad standard [28–30]. Popularity of 802.11ad versus other 60 GHz wireless standards can also be seen from the results of Google Trends data taken between December 2014 and December 2017 [31].

802.11ad supports multi-channel communication, where the number of maximum channels differ according to the region/country. Table 1 summarizes the number of non-overlapping channels and frequency allocation in different regions. Non-overlapping multiple channels enable simultaneous communication in different links in the same environment, consequently increase the overall throughput achievable in the network. Some characteristics of 802.11ad channels are given in Fig. 1.

Like 2.4 GHz Wi-Fi, 60 GHz 802.11ad is a multi-channel specification, however, channel widths and spectrum frequency are the key differences between them. Channel width of 802.11ad is around 100 times wider than 2.4 GHz Wi-Fi's. These characteristics ensure higher bandwidth in 802.11ad.

Another aspect of 60 GHz RF communication is the lack of long-range communication. As indicated by free space path loss model ($FSPL$) in Eq. (1), due to higher carrier frequency used in 802.11ad, which is 60 GHz, larger path loss is experienced compared to WiFi band, and therefore 802.11ad transmitters have a shorter communication range, which is around 10 m. Additionally, signals at such high frequencies cannot penetrate through walls. They are affected even from small objects and need line-of-sight paths.

Table 2
10 Gigabit Ethernet (10 GbE) vs. millimeter wave [27].

Feature	10 GbE	mm-wave
Link speed (Gbps)	2–10	5–7
Bit error rate	10^{-13}	10^{-12}
Switching latency (μs)	1.5	0.3
Communication range (m)	400–2000	10
Energy Consumption (J/Gb)	2.5–7.3	0.35

As it seems that short communication range is a disadvantage for an office and home network, it has some advantages for DC networks. Firstly, short range communication makes very hard to overhear traffic outside of DC, which provides security. Secondly, short range communication prevents unwanted interference from other communicating nodes, i.e., from transmitters on servers or racks. Although 10 m of range seems limited for communication in a DC network, [16] shows that it can span about 70 racks, which can host hundreds of servers. Therefore mm-wave technology is suitable for DCNs as an alternative or supporting technology to wired communication. Table 2 shows the comparison of 10 Gigabit Ethernet (10 GbE) and mm-wave wireless technologies (IEEE802.15.3c) according to 60 GHz transceiver design simulation results given in [27]. Although mm-wave has a lower communication range, as discussed before, it is not a problem for data center networks and also it has advantages like security. It is seen that link speed of IEEE802.15.3c is similar with 10 GbE, and it has 5 times lower switching latency. The reason behind high energy consumption rate of Ethernet is using powerful switches. Also bit error rate of mm-wave is 10 times higher than Ethernet, in overall, it is agreed that using 60 GHz technology is a feasible solution for data center networks.

$$FSPL = \left(\frac{4\pi d f}{c}\right)^2 \quad (1)$$

where:

d	=	Distance between transmitter and receiver (m)
f	=	Signal frequency (Hz)
c	=	Speed of light (m/s)

Next we survey the studies on data center network designs that use 60 GHz wireless links partially or completely.

3. Wireless data center networks

Use of 60 GHz transmission is investigated in [32] and it is shown that 60 GHz wireless links can support multi-Gbps data-rate over short distances. The work of Ramachandran et al. [33] is the first study that proposed use of 60 GHz wireless transmission in data center networks and showed its feasibility. After that, a lot of research studies are done on this topic. However, there are still a lot of issues that are unresolved and need investigation. Meanwhile, the 60 GHz 802.11ad [23] wireless standard is published.

We consider the research studies done on wireless data centers (WDCs) in two categories:

(1) Hybrid Data Centers (HDCs), which exploit the underlying wired infrastructure of a data center and augment it with wireless links (Fig. 2),
(2) Completely Wireless Data Centers (CWDCs), which completely remove all communication cables and provide a fully wireless topology.

Fig. 2 shows an example about how wired links can be augmented with wireless links in a data center. As can be seen, all existing wired links and network nodes are preserved and wireless equipments are added on top of the existing infrastructure. The main idea is augmenting oversubscribed wired links with the help of wireless radios when hot node congestion occurs. In case of a congestion, servers or ToR

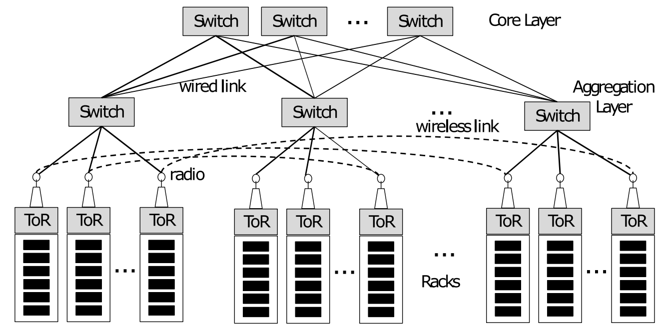

Fig. 2. Hybrid data center illustration where wireless radios are placed on top of racks.

switches on a congested path can directly communicate with each other wirelessly to relieve hot spots [34]. Such on-demand wireless links are called *flyways*.

HDCs typically focus on dealing with hot nodes that send and receive more traffic and cause the network to be congested. By using wireless flyways, these hot nodes can start using wireless communication and in this way congestion can be decreased and network throughput can be increased [16,30]. On the other hand, CWDC solutions focus on designing a complete wireless topology by placing wireless units as optimal as possible and by proposing wireless routing and scheduling schemes [35,36].

Although HDCs seem to be more feasible and economical for now, CWDCs are more innovative and futuristic. In CWDCs, communication cabling cost, which reaches up to 7%–8% of total infrastructure cost [37], is eliminated. Additionally, infrastructure complexity and maintenance problems due to cabling are reduced. We need to consider wireless equipment cost, but this can be compensated by the reduction in number of switches used.

In the following subsections, works on HDCs and CWDCs are studied separately. Works that cannot be classified as HDC or CWDC are discussed in the Other Studies subsection.

3.1. Hybrid Data Centers (HDCs)

In this section various HDC designs will be presented. 3D Beamforming HDCs are grouped in the next subsection, and then other designs will be presented.

3.1.1. Hot node congestion elimination

The work by Kandula et al. [16] propose adding 60 GHz wireless flyways to overcome hotspots (hot node congestion) in a wired DC by placing a wireless transceiver on top of each rack to communicate with other racks. A matrix of application demands is derived by instrumenting 1500 servers and monitoring the respective traffic to identify hot nodes and communication patterns. The paper observes that although the traffic demand matrix is sparse and only a few ToR switches are congested, adding wireless links to a DCN increases network throughput noticeably. They also state that adding flyways is likely to be a cost-effective in many cases. This work is the first one in literature that proposes a wireless data center design.

In [38] Cui et al. propose a wireless solution for hot node congestion elimination by using a genetic algorithm to solve the channel allocation problem. They extend their work in [15] by giving a formulation of the hot node congestion problem caused by a few hot nodes. They focus on the problem of scheduling of wireless transmissions, which is independent of the implementation.

Halperin et al. [30] propose relieving hot nodes in oversubscribed networks using millimeter-wave communication as a hybrid solution that use directional antennas. Antenna types and details like radiation

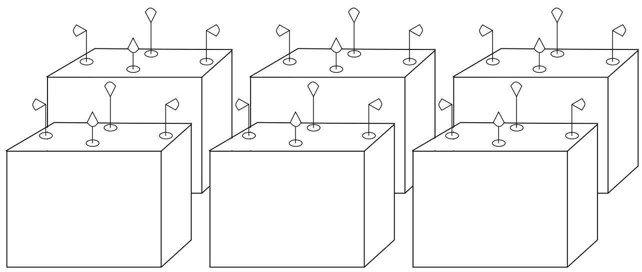

Fig. 3. Wireless antenna placement.

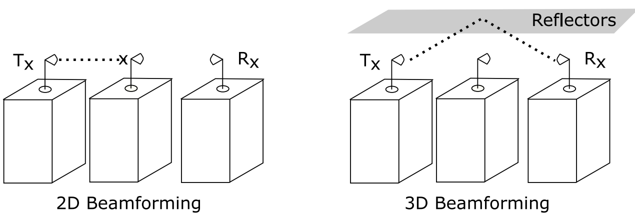

Fig. 4. 2D and 3D beamforming.

patterns are also given in the paper. The paper did a detailed 802.11ad simulation using ns3 and made their code publicly available. PHY and MAC design implementation, signal propagation, bit error rate (BER) and signal-to-interference-plus-noise ratio (SINR) models are implemented in their simulator for 802.11ad directional antennas.

Different than other HDC solutions, [34] proposes using four antennas per rack (one for each neighbor) in a data center topology, as seen in Fig. 3. In this way they try to eliminate the hotspots, and they verify their proposal using a customized simulator.

3.1.2. 3D beamforming HDCs

Zhang et al. [39] suggest using metal reflectors to avoid obstacles and to provide line-of-sight path for better communication. They report that obstacles larger than 2.5 mm may affect communication due to the fact that signals used in 60 GHz technology have around 5 mm wavelength. Therefore, rather than using direct links between racks, they use reflectors to circumvent other wireless antennas that may obstruct the communication. This is called as 3D Beamforming and is illustrated in Fig. 4.

[28] proposes a 3D Beamforming strategy using mirrors and show the advantage of 3D Beamforming over 2D Beamforming via simulation experiments. It states that due to the limited top-of-the-rack area (4ft × 2ft) defined by the current rack standards, at most eight (each occupying a 1ft × 1ft area) 60 GHz transceivers can fit on a single rack.

Like [28,40] proposes a 3D beamforming technique named Graphite to eliminate transmission blocking problems caused by antennas placed at the same-height. However, they did not place reflectors on the ceiling as done in [28]. Instead they suggest using rotatable and liftable crank arms as seen in Fig. 5. With that Graphite is not affected by ceiling height and quality. They show that Graphite is a feasible solution for wireless DCNs and compare their solution with Flyways [16] and 3D Beamforming [40].

3.1.3. Diamond topology

Cui et al. [41,42] proposed an interesting HDC architecture called Diamond topology. They suggest equipping each server with an antenna and using reflectors to provide communication while decreasing interference. They present a new routing algorithm for their architecture. Nodes can also benefit from multiple-reflections, which can increase the communication range.

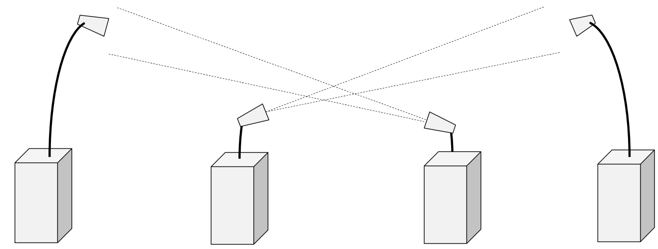

Fig. 5. 3D beamforming using crank arms.

3.1.4. Dynamic link scheduling

In [43] and [44], methods for dynamically scheduling wireless transmissions considering traffic demands are proposed. [44] proposes a wireless DCN architecture and a distributed wireless link scheduling mechanism. Two heuristics are proposed for unbalanced traffic distribution and to maximize total network utility.

3.1.5. Multicast traffic

Yu et al. [45] and Chuang et al. [46] present wireless DCN solutions for multicast traffic used in cloud services to coordinate applications. They define a multicast tree problem that tries to minimize the total multicast data traffic. They show that the problem is NP-hard and present a heuristic algorithm. They propose a formulation for the multicast tree construction problem using wired and wireless links where antennas are placed on top of the racks. They performed simulations with real data, and the results show that redundant data transmissions in the network can be reduced.

3.1.6. Other HDCs

Katayama et al. [18] present another HDC topology using wireless transceivers on top of each rack supporting multi-hop communication. They propose a robust wireless packet switching network exploiting line-of-sight links. [47] also proposes a novel wireless HDC architecture, called RF-HYBRID, to increase total network throughput.

In a more recent work, Han et al. [48] proposes a greedy heuristic to jointly route flows and schedule transmissions to minimize network congestion. They perform simulation experiments in ns3.

A recent work by Francois [29] proposes a novel hybrid data center design named ToR Level Completely Wireless. The design uses completely wireless single-hop links for inter-rack communication and traditional wired links for intra-rack communication.

This design eliminates high-cost core level switches, which consume a lot of energy. Additionally, long cables to connect ToR switches to core level switches are eliminated as well. Thus cabling and cooling costs are substantially reduced. In a wired datacenter the extent the cabling complexity reaches can be daunting. Such a complex cabling increases the cost of cooling and maintenance as well.

[49] proposes a coflow and antenna scheduling for hybrid server-centric DCNs. They formulate the scheduling problem as an optimization problem and show that it is NP-hard. Therefore, they use a heuristic method. They assume the servers are placed in a 3D torus topology.

A recent work by Zhu et al. [50] proposes algorithms for multi-channel and multi-radio wireless DCNs. They consider a multi-rooted fat-tree like topology. Additionally, conflict graphs are used for modeling interference relationship among wireless links. Also, related with HDCNs, [51] and [52] propose facility scheduling in DCNs that use wireless links established via 60 GHz radios placed on top of racks.

All these works augment a wired network structure with wireless links to eliminate congestion and increase throughout. They are, however, incremental in their approach to solve congestion and capacity

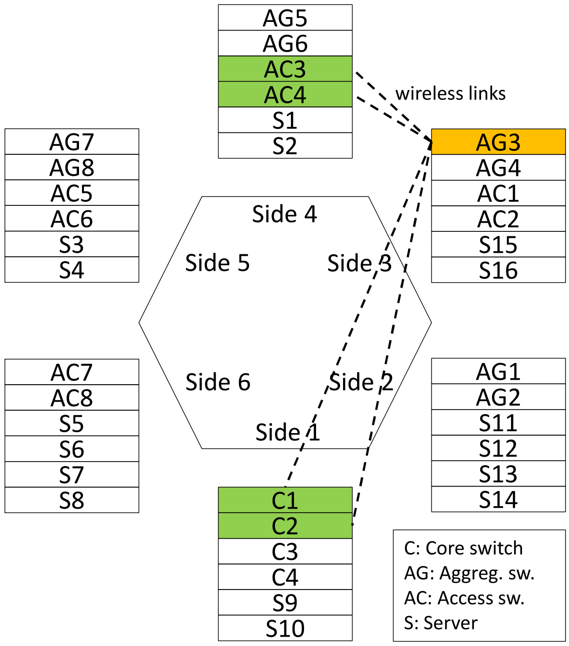

Fig. 6. Hexagonal placement of racks in [27] and an example of wireless links of AG3 are shown in green for the topology given in Fig. 7. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

problems. Next, we explore studies that follow a more radical approach and just use wireless links to build a DC network.

3.2. Completely Wireless Data Centers (CWDCs)

There are various innovative design alternatives for Completely Wireless Data Centers (CWDCs). They differ in various aspects, like server and rack design, usage of multi-hop communication, where antennas are placed, how many radios per server or communication unit are used, etc. Polygonal WDCNs and 3D Beamforming in WDCNs are described in the following subsections, and then other designs will be presented.

3.2.1. Polygonal WDCNs

Vardhan et al. [35] propose a Completely Wireless Data Center design by removing all data cables (wires) and equipping all servers with wireless transceivers. Regarding the wireless links to be established in the network to carry traffic, they propose to emulate a wired fat-tree topology using polygonally arranged wireless servers. They also propose a node placement algorithm for this emulation.

Like [35], the studies in [27,53], and [54] propose a polygonal arrangement of a CWDC using beam-forming and phased array antennas, as seen in Fig. 6. Proposed wireless DCNs in these papers are completely wireless and use 802.15.3c radios. Unlike [36], solutions in [27,35,53], and [54] do not propose a new server and rack design, and use the conventional racks and servers. However, rather than using the wired backbone of a traditional DCN, they remove all the wires and place the racks on sides of a polygon, e.g., a hexagon (Fig. 6). Servers in a story can communicate with servers in different racks if their stories are close enough. For example, a server at the bottom story cannot communicate with servers placed at higher stories.

Assigning two radios per server can guarantee reaching all other servers placed in different racks. Vardhan et al. emulate a wired 4-pod fat-tree topology and they propose a simple algorithm specific for this fat-tree using mm-wave wireless communication links. In fat-tree

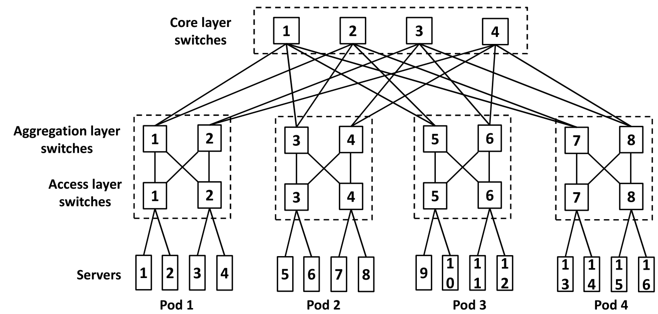

Fig. 7. Wired 4-pod Fat-tree architecture [27].

Table 3
Cost analysis of wireless antennas [54].

k	$C_{Switch}(k)$	$C_{Fat-tree}$	C_{WDCN}	C_{TX} (Estimated)
16	2000	640k	4096CTX	78
24	4000	2.8M	6912CTX	202
32	6000	7.68M	16384CTX	234
48	7500	21.6M	55296CTX	390
96	70 000	806.4M	442368CTX	911

topology, aggregation and access layer switches are grouped as pods. For a k-pod fat-tree, every pod has k/2 aggregation and k/2 access layer switches. As seen in 4-pod fat-tree in Fig. 7, there are 2 aggregation and 2 access layer switches in each pod. Core switches are connected to these pods with aggregation switches.

In this emulated topology, all network nodes (servers or routers) in Fig. 7 are placed in racks in such a way that every node can reach its one-hop wired neighbor directly with a wireless link. For example, access router 2 (AC2) has four wired neighbors: aggregation routers 1, 2, and servers 3, 4. In the emulated scenario, AC2 is placed in Side 3 of the polygonal DC layout and its neighbors are placed in stories on Sides 2 and 5, where they are reachable from AC2.

Vardhan also performs a cost analysis for 60 GHz transceivers by comparing the cost of a completely wireless DCN with the switching cost of a wired DCN that has Fat-tree topology. He estimates the cost of one wireless transceiver using standard switch costs. Cost analysis is given in Table 3. In this analysis, k is the number of pods in a Fat-tree structure, $C_{switch}(k)$ is the cost of switches for a k-port switch, $C_{Fat-tree}$ is the cost of k-pod DCN, C_{WDCN} is the cost of WDCN assuming two transceivers per node. The last column, C_{TX}, is the estimated cost of a single 60 GHz transceiver calculated by $C_{TX} = \frac{C_{Fat-tree}}{N_{TX}}$, where N_{TX} is the total number of transceivers used in WDCN. This analysis shows that if the cost of a 60 GHz transceiver becomes less than C_{TX}, completely wireless DCN will cost less than wired DCN.

Also, in [55], authors argue that creating completely wireless interconnect is viable and they present mathematical proofs.

3.2.2. 3D beamforming in WDCNs

Zhu et al. propose a new low-latency facility network, called Angora [56], that uses a completely wireless solution using 60 GHz 3D beamforming. Fixed antenna directions are used for a given topology, assuming that the topology of data centers are not changed frequently. Their solution supports multi-hop communication for a constant number of hops. They verify their solution using a testbed and perform also simulation experiments considering both horn antennas and antenna arrays.

In [57], Zhao and Tan presented a novel DC design including intra-rack and inter-rack architecture which outperforms Cayley data centers in terms of bandwidth using mirrors placed on ceiling.

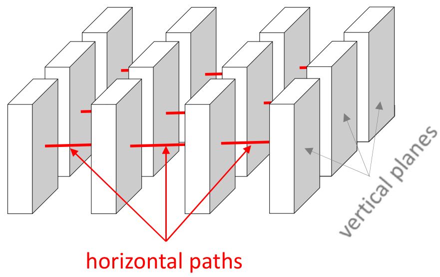

Fig. 8. Rack arrangement in [59], where red paths indicate horizontal wireless paths, and gray planes indicate vertical planes for communication of servers. All servers are capable of communicating via their respective horizontal line and vertical plane.

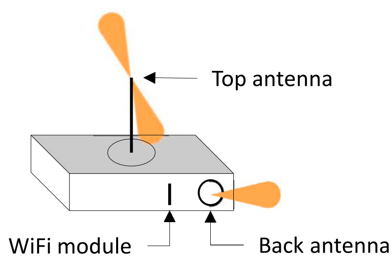

Fig. 9. Antenna placement in [59].

3.2.3. Other WDCNs

Shin et al. [36] propose a novel CWDC design using Cayley Graphs. In this work, they propose a new prism shaped container design and a cylindrical rack design. Servers are equipped with two transceivers, one is placed at the inner circle of the cylinder to provide intra-rack communication, and the other is placed at the outer circle of the cylinder for inter-rack communication. Servers inside a cylindrical rack can communicate with servers in the same rack via intra-rack transceivers if their stories are not far away. By exploiting Cayley data center topology, multi-hop routing is also possible. Interference measurements and simulation results evaluating the performance of the proposed architecture are also provided.

As a new completely wireless architecture, [58] suggests a spherical rack design, and performs simulations for map-reduce applications in a WDC.

In [59] and [60], a new CWDCN is proposed by preserving regular rectangular arrangement in conventional DCNs. Fig. 8 shows this arrangement and illustrates horizontal wireless paths and vertical plane used in 60 GHz wireless communication. Each server is equipped with one Wi-Fi antenna and two high-gain 60 GHz antennas placed on top and back of a server (Fig. 9). Back antenna is used for intra-rack communication or one-hop communication with a server in the same vertical plane, and top antenna is used for one-hop communication with a server in the same horizontal wireless path. If destination cannot be reached, the solution also supports two-hop communication using an intermediate server in the same horizontal line with the sender and same vertical plane with the receiver using a routing method called horizontal-first routing. Also, Wi-Fi transceivers are used for exchanging control information to coordinate 60 GHz data traffic. Compared with wired fat-tree network and ToR-ToR WDCN, this proposed solution reduces energy consumption by utilizing direct server to server wireless links.

3.3. Other studies

Yamane et al. [61] and Katayama et al. [62] present interference cancellation algorithms and link design strategies for MIMO systems in WDCs.

Since 802.11ad supports multi-channel wireless communication, [63] and [64] investigate channel measurements and characterization, channel path-loss and delay spread in WDCNs. Also, [63] shows initial results for 60 GHz Wireless Data Centers in a real testbed.

In Table 4, we are summarizing the key features of the studies that we discussed in this paper. For each study, we indicate whether it is about a hybrid (H) or a completely wireless (C) solution, whether it is using a testbed (T) or simulation (S) for evaluation, and when the paper is published. Additionally, we present the key features and keywords of the study by listing them in a separate column.

4. Summary and conclusions

Although wireless DCNs are not used in commercial data centers yet, the idea of using wireless DCNs is promising. As surveyed in this paper, there are a lot of research studies done on this subject over the past 10 years. This is an emerging technology with a great potential.

60 GHz wireless communication technology is quite widely used and it provides the necessary bandwidth and flexibility to support high-rate and dynamic data center traffic. With careful design, it can increase throughput, decrease congestion and enable dynamic scheduling. Although communication at this extremely high frequency band has lower communication range, i.e., around 10 m, many studies show that it is feasible for WDCNs. In fact such a short range communication can bring advantages for conventional DCNs, since short-range transmission can reduce or prevent overhearing and can reduce interference on other receivers. Free space optics technology is also an alternative to realize wireless DCNs, however, we left it out of the scope of this work to be able to focus more on RF communication.

We categorized the research work on wireless data centers into two: studies on hybrid data centers (HDCs) and studies on Completely Wireless data centers (CWDCs). In HDCs, both wired and wireless links are used for communication, and mostly wired infrastructure is preserved as it is, and wireless links are used additionally to decrease hot node congestion. Congested nodes and links are dynamically configured to use wireless links that are established on the fly. Preserving existing wired backbone makes HDCs more feasible and economical than CWDCs in short term.

In CWDCNs, communication is provided by only wireless links, and therefore network topology used in conventional wired data centers cannot always be used for CWDCs. Some studies change both the topology and server/rack designs, and some preserve the conventional rack design by only changing the placement of the racks. In both approaches, servers are equipped with one or more wireless transceivers to provide fully wireless communication.

Wireless DCNs are not a very mature topic yet, even though it has been around 10 years since the first paper has appeared on this area. Although there are some papers, multi-hop routing in WDCNs needs more investigation. Additionally, channel allocation methods need to be developed to effectively use multiple channels available in the communication standard.

CRediT authorship contribution statement

Caglar Terzi: Conceptualization, Methodology, Investigation, Writing - original draft, Visualization. **Ibrahim Korpeoglu:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 4
Comparison of WDCN papers. *H: Hybrid, C: Completely Wireless, T: Testbed, S: Simulation*.

Reference	Year	H/C	T/S	Key features
Smulders et al. [32]	2007	–	–	– 60 GHz transmission is introduced
Ramachandran et al. [33]	2008	–	–	– Pioneer work for 60 GHz WDCNs – Shows feasibility of using wireless communication in DCNs – Cable complexity costs 7%–8% of total cost
Kandula et al. [16]	2009	H	S	– Overcomes hotspot problem
Vardhan et al. [35]	2010	C	–	– Emulates fat-tree and 3-tier architectures – Polygonal WDCN topology is used
Halperin et al. [30]	2011	H	S	– Relieving hotspots in oversubscribed networks – Directional antennas used to decrease interference – NS-3 code is given for simulation – Transmitters on top of server racks – 802.11ad technology based
Zhang et al. [39]	2011	H	S	– 3D beamforming is used – Ceiling reflects signals
Cui et al. [44]	2011	H	S	– Proposes a new WDCN architecture – Wireless link scheduling mechanism is given – Proposes two heuristics for unbalanced traffic distribution – Maximizes total network utility – Distributed wireless scheduling is proposed – Multi-radio devices are used
Katayama et al. [18]	2011	H	–	–Multi-hop topology is used – Transmitter on top of server racks
Cui et al. [43]	2011	H	S	– Dynamically schedules wireless transmissions based on traffic demand
Yamane and Katayama [61]	2012	–	S	–Interface cancellation algorithm is given – Distributed MIMO systems are used
Katayama et al. [62]	2012	–	–	– MIMO Link Design Strategy is proposed
Zhou et al. [28]	2012	H	T + S	– 3D beamforming is utilized – Ceiling reflections is utilized – Simulations of 2D vs 3D beamforming are done – Multi-radio devices are used – 802.11ad technology based
Shin et al. [36]	2012	C	S	– Cayley graphs are used – Cylindrical racks are proposed – New topology is proposed
Cui et al. [15], [38]	2013	H	S	– Genetic algorithm based solution – Channel allocation problem is solved – Attacks hot node congestion elimination optimization problem formulation – Focuses on scheduling problem of wireless transmission
Vardhan et al. [27]	2013	C	S	– Beamforming is utilized – Phased array antennas are assumed – Polygonal arrangement is proposed – Emulates DC topology – Cost comparison done between wired vs wireless DCs – 802.15.3c technology based – No need to build new racks or servers – Conventional racks placed in a different way, i.e., polygonal
Huang et al. [47]	2013	H	S	– Collaborated hybrid DC architecture is proposed
Vardhan and Prakash [55]	2013	C	–	– Shows that creating completely wireless interconnect is viable – Investigation based on mathematical equations
Yu et al. [45]	2013	H	S	– Multicast is considered – Heuristic algorithm and formulation – Multicast tree building problem for wired + wireless links – Simulations using real data – Results show that total data redundancy is reduced – Top of server rack transmitters assumed
Zhu et al. [56]	2014	C	T + S	– Low latency facility network is proposed – 60 GHz beamforming radios are used – 3D Beamform is utilized – Multi-hop (constant-hop) paths are considered – Fixed antenna direction is used for a given topology – Transmitters on top of server racks
Shan et al. [34]	2014	H	S	– Neighborways, i.e., 4 antennas are placed in each rack – Simulation are done in MATLAB – Hotspot are tried to eliminated – Transmitters on top of server racks

(*continued on next page*)

Table 4 (*continued*).

Reference	Year	H/C	T/S	Key features
Zaaimia et al. [63]	2014	–	T	– Initial results of 60 GHz wireless DC in a real data center – Channel measurement is conducted
Vardhan and Prakash [53]	2014	C	S	– TDMA scheduling is used – Polygonal WDCN topology is used – C++ simulations are done
Zhao and Tan [57]	2014	C	S	– Novel DC design is proposed including intra-rack and inter-rack architecture – Outperforms Cayley DC – Mirrors are placed on ceiling – 3D Beamforming is utilized
Vardhan [54]	2014	C	S	– Polygonal WDCN topology is used
Baccour et al. [6]	2015	–	–	– Survey about WDCNs – Power consumption related information is given
Han et al. [48]	2015	H	S	– Minimizes network congestion – Jointly routing flows and scheduling wireless antennas – Simulations are done in NS-3 – Greedy heuristic is proposed
Chuang et al. [46]	2015	H	S	– Minimizes multicast traffic – Multicast tree is constructed – 1 antenna per rack is used – Transmitters on top of server racks
Suto et al. [58]	2015	C	S	– Spherical rack architecture – Simulations are done for map-reduce
Zaaimia et al. [64]	2015	H, C	T	– 60 ghz channel measurement and characterization – Channel path-loss and delay spread
Francois [29]	2016	H	S	– ToR level completely wireless – Single-hop rack-to-rack communication
Cui et al. [41], [42]	2016	H	T + S	– Antennas are placed on each server – Proposes a new topology – Diamond shaped topology – Customized simulator is used
Hamza et al. [19]	2016	–	–	– Survey about WDCNs
Li and Santini [49]	2017	H	S	– Hybrid server centric DCNs – Heuristic algorithm is presented for coflow and antenna scheduling – 3D torus network topology is proposed – OMNet++ and Gurobi are used
Zhang et al. [40]	2017	H	T + S	– Transmitters on top of server racks – New hybrid topology (Graphite) is proposed – 3D Beamforming using liftable and rotatable crank arm – Comparison with [16] and [28]
Wei and Sun [51], [52]	2017	H	S	– Extends NS3 code given in [30] – Wireless facility scheduling algorithm is proposed
Xia et al. [65]	2017	–	–	– Survey about DCNs, including some WDCN papers
Umamaheswaran et al. [59]	2017	C	S	– Single-hop and 2-hop communication – Extends NS3 code given in [30] – Reducing power consumption using CWDCN – Completely wireless network proposed by maintaining regular rectangular arrangement – Two 60 GHz antennas per server, one for horizontal path and one for vertical plane – Compared with fat-tree and ToR-ToR wireless DCN
Zhu et al. [50]	2018	H	S	– Multicast, multichannel communication – Simulations are written in C – Directional antennas are used with narrow beam – Multi-rooted tree like fat-tree – Contradiction graph are used
Jing et al. [66]	2020	C	–	– WDCN design for ExCCC networks is proposed – Transceivers are placed on top of each rack in different heights
Cao et al. [67]	2020	–	–	– Radio propagation pattern is modeled – Interference is modeled – Topology optimization problem is studied
Wang et al. [68]	2020	H	S	– Inter-Rack First Multicast implementation is proposed – NS3 simulations are used
Zhang et al. [69]	2020	–	–	– New DC network topology named as Comb is proposed – Wireless antennas are placed in different levels – Multicast routing algorithm is proposed for Comb topology

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