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Architectures of Data Center Networks: Overview

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Abstract

To deal with the widespread use of cloud services and the unprecedented traffic growth, the scale of the Data Center has importantly increased. Therefore, it is crucial to design novel efficient network architectures able to satisfy the requirements on bandwidth. As a key physical infrastructure, Data Center Network (DCN) designing has widely been a hot research focus.

This chapter reviews the main DCN architectures propounded in the literature. To do so, a taxonomy of DCN designs will be proposed, while analyzing in depth each structure of the given classification. Then, we will provide a qualitative comparison between these different DCN groups. Finally, we will present hybrid DCN architecture based on wired and wireless architecture.

1.1 Taxonomy of DCN Architectures

In this section, we present a taxonomy of the existent Data Center Network (DCN) architectures with a detailed review of each drawn class. In general, several criteria have to be considered to design robust DCNs, namely, high network performance, efficient resource utilization, full available bandwidth, high scalability, easy cabling, etc. To deal with the aforementioned challenges, a panoply of solutions have been designed. Mainly,

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we can distinguish two research directions. In the first one, wired DCN architectures have been upgraded to build advanced cost-effective topologies able to scale up data centers. The second approach has resorted to deploying new network techniques within the existing DCN so as to handle the challenges encountered in the prior architectures. Hereafter, we will give a detailed taxonomy of these techniques.

1.1.1 Classification of DCN Architectures

With regard to the aforementioned research directions, we can identify three main groups of DCN architectures, namely, **switch-centric** DCN, **server-centric** DCN, and **enhanced** DCN. Each group includes a variety of categories that we will detail hereafter.

- *Switch-centric DCN architecture*: switches are, mostly, responsible for network-related functions, whereas the servers handle processing tasks. The focus of such a design is to improve the topology so as to increase network scale, reduce oversubscription, and speed up flow transmission. Switch-centric architectures can be classified into three main categories according to their structural properties:
    1. *Traditional tree-based DCN architecture*: represents a specific kind of switch-centric architecture, where switches are linked in a multirooted form.
    2. *Hierarchic DCN architecture*: is a switch-centric DCN, where network components are arranged in multiple layers. Each layer characterizes traffic differently.
    3. *Flat DCN architecture*: compresses the three switch layers into only one or two switch layers, in order to simplify the management and maintenance of the DCN.
- *Server-centric DCN architecture*: servers are enhanced to handle networking functions, whereas switches are used only to forward packets. Basically, servers are simultaneously end-hosts and relaying nodes for multihop communications. Usually, server-centric DCN are recursively defined multilevel topologies.
- *Enhanced DCN architecture*: is a specific DCN which is tailored for future Cloud computing services. Indeed, the future research direction attempts to deploy networking techniques so as to deal with wired DCN designs limitations. Recently, a variety of technologies have been used in this context, namely, optical switching and wireless communications. Accordingly, we distinguish two main classes of enhanced DCN architectures:

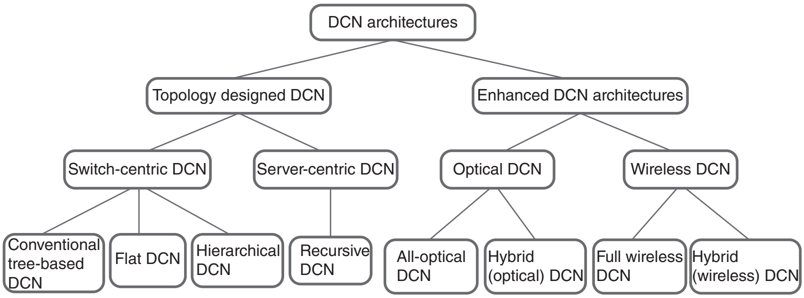

Figure 1.1 Taxonomy of DCN architectures.

1. *Optical DCN*: makes use of optical devices to speed up communications. It can be either: (i) all-optical DCN (i.e. with completely optical devices) or (ii) hybrid optical DCN (i.e. both optical and Ethernet switches).
2. *Wireless DCN*: deploys wireless infrastructure in order to enhance network performance, and may be: (i) fully wireless DCN (i.e. only wireless devices) or (ii) Hybrid DCN (i.e. both wireless and wired devices).

Figure 1.1 illustrates the taxonomy of current DCN architectures. In the following, we will detail each category and discuss their impact on Cloud computing performance.

1.1.2 Switch-Centric DCN Architectures Overview

1.1.2.1 Tree-Based DCN

The traditional DCN is typically based on a multiroot tree architecture. The latter is a three-tier topology composed by three layers of switches. The top level (i.e. root) represents the core layer, the middle level is the aggregation layer, while the bottom level is known as the access layer. The core devices are characterized by high capacities compared with aggregation and access switches. Typically, the core switches' uplinks connect the data center to the Internet. On the other hand, the access layer switches commonly use 1 Gbps downlink interfaces and 10 Gbps uplink interfaces, while aggregation switches provide 10 Gbps links. Access switches (i.e. top of rack, ToRs) interconnect servers in the same rack. Aggregation layer allows the connection between access switches and the data forwarding. It is worth noting that the above values of network interface cards throughput are continuously increasing. For instance, nowadays it is easy and not really expensive

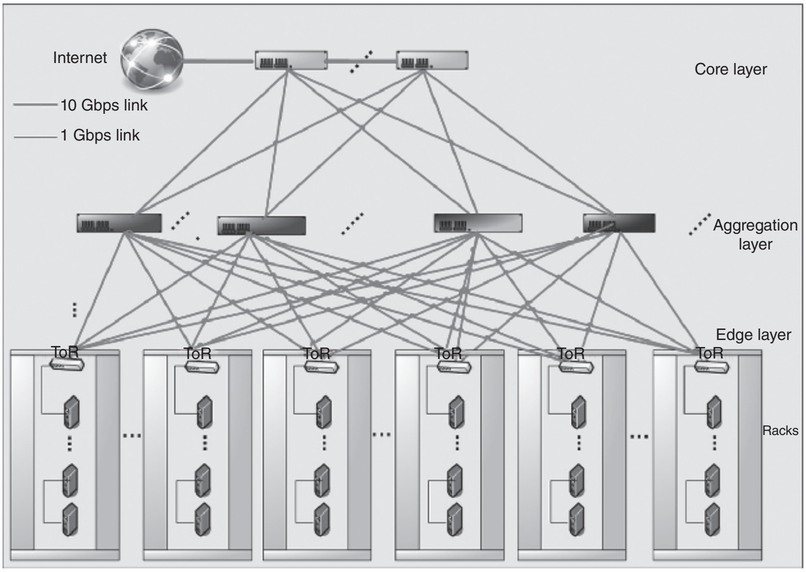

Figure 1.2 Traditional tree-based DCN architecture.

to deploy interfaces with 25 and 100 Gbps. An illustration of tree-based DCN architecture is depicted in Figure 1.2.

Unfortunately, traditional DCNs struggle to resist to the increasing traffic demand. First, core switches are prone to bottlenecks issues as soon as the workloads reach the peak. Moreover, in such a DCN, several downlinks of a ToR switch share the same uplink which limits the available bandwidth. Second, DCN scalability strongly depends on the number of switch ports. Therefore, the unique way to scale this topology is to increase the number of network devices. However, these solutions results in high construction costs and energy consumption. Third, tree-based DCN suffers from serious resiliency problems. For instance, if a failure happens on some of the aggregation switches, then servers are likely to lose connection with others. In addition, resource utilization is not efficiently balanced. For all the aforementioned reasons, researchers put forward alternative DCN topologies.

1.1.2.2 Hierarchical DCN Architecture

Hierarchical topology arranges the DCN components in multiple layers. The key insight behind this model is to reduce the congestion by minimizing the oversubscription in lower-layer switches using the upper-layer devices. In the literature, we find several hierarchic DCN examples, namely, CLOS, FatTree, and VL2. Hereafter, we will describe each one of them.

CLOS-Based DCN Is an advanced tree-based network architecture. It was, first, introduced by Charles Clos, from Bell Labs, in 1953 to create nonblocking multistage topologies, able to provide higher bandwidth than a single switch. Typically, CLOS-based DCNs come with three layers of switches: (i) access layer (ingress), composed of the ToRs switches, directly connected to servers in the rack; (ii) aggregation layer (middle), formed by aggregation switches referred as spines and connected to the ToRs; and (iii) core layer (egress), formed by core switches serving as edges to manage traffic in and out the DCN (Chen et al., 2016).

The CLOS network has been widely used to build modern IP fabrics, generally referred to as spine and leaf topologies. Accordingly, in this kind of DCN, commonly named folded-CLOS topology, the spine layer represents the aggregation switches (i.e. spines), while the leaf layer is composed of the ToR switches (i.e. leaves). In other words, in CLOS topology, (i) leaf layer is composed of ToR switches and (ii) spine layer is composed of aggregation switches. The spine layer is responsible for interconnecting leafs. CLOS inhibits the transition of traffic through horizontal links (i.e. inside the same layer). Moreover, CLOS topology scales up the number of ports and makes possible huge connection using only a small number of switches. Indeed, augmenting the switches ports enhances the spine layer width and, hence, alleviates the network congestion. In general, each leaf switch is connected to all spines. In other words, the number of up (respectively, down) ports of each ToR is equal to the number of spines (respectively, leaves). Accordingly, in a DCN of n leaves and m spines, there are $n \times m$ wired links. The main reason behind this link redundancy is to enable multipath routing and to mitigate oversubscription caused by the conventional link state open shortest path first (OSPF) routing protocol. In doing so, CLOS network provides multiple paths for the communication to be switched without being blocked.

CLOS architecture succeeds to ensure better scalability and path diversity than conventional tree-based Data Center (DC) topologies. Moreover, this design reduces bandwidth limitation in aggregation layer. However, this architecture requires homogeneous switches and deploys huge number of links.

Fat-Tree DCN Is a special instance of CLOS-based DCN introduced by Al-Fares et al. (2008) in order to remedy the network bottleneck problem existing in the prior tree-based architectures. Specifically, Fat-Tree comes with a new way to interconnect commodity Ethernet switches. Typically, it is organized in k pods, where each pod contains two layers of $k/2$ switches. Each k-port switch in the lower layer is directly connected to $k/2$ hosts, and to $k/2$ of the k ports in the aggregation layer. Therefore, there is a total of

$(k/2)^2$ k-port core switches, each one is connected to each port of the k pods. Accordingly, a Fat-Tree built with k-port switches supports $k^3/4$ hosts.

The main advantage of the Fat-Tree topology is its capability to deploy identical cheap switches, which alleviates the cost of designing DCN. Further, it guarantees equal number of links in different layers which inhibits communication blockage among servers. In addition, this design can importantly mitigate congestion effects thanks to the large number of redundant paths available between any two given communicating ToR switches. Nevertheless, Fat-Tree DCN suffers from complex connections, and its scalability is closely dependent on the number of switch ports. Moreover, this structure is impacted by the possible lower-layer devices failure which may entail the degradation of DCN performance.

This architecture has been improved by designing new structures based on a Fat-Tree model, namely, **ElasticTree** Heller et al. (2010), **PortLand** Mysore et al. (2009), and **Diamond** Sun et al. (2014). The main advantage of such topologies is to reduce maintenance cost and enhance scalability by reducing the number of switch layers.

Valiant Load Balancing DCN Architecture Valiant load balancing (VLB) is introduced in order to handle traffic variation and alleviate hotspots when random traffic transits through multipaths. In the literature, we find, mainly, two kinds of VLB architectures. First, **VL2** is three-layer CLOS architecture introduced by Microsoft in Greenberg et al. (2009a). Contrarily to Fat-Tree, VL2 resorts to connecting all servers through a virtual two-layer Ethernet, located in the same local area network (LAN) with servers. Moreover, VL2 implements VLB mechanism and OpenFlow to perform routing while enhancing load balancing. To forward data over multiple equal cost paths, it makes use of equal-cost multi-path (ECMP) protocol. VL2 architecture is characterized by its simple connection and does not require software or hardware modifications. Nevertheless, it still suffers from scalability issue and does not take into account reliability, since single node failure problem persists.

Second, **Monsoon** architecture (Greenberg et al., 2008), aims to alleviate over-subscription based on a two-layer network that connects servers and a third layer for core switches/routers. Unfortunately, it is not compatible with the existing wired DCN architecture.

1.1.2.3 Flat DCN Architecture

The main idea of the Flat switch-centric architectures is to flatten down the multiple switch layers to only two or one single layer, so as to simplify maintenance and resource management tasks. There are several topologies that are proposed for this kind of architecture. First, the authors of Abts et al. (2010) conceive flattened butterfly (**FBFLY**) architecture to build energy-aware DCN. Specifically, it considers power consumption proportionally to the traffic load, and so replaces the 40 Gbps links by several links with fewer capacity regarding the requested traffic in each scenario. colored butterfly (**C-FBFLY**) Csernai et al. (2015) is an improved version of FBFLY which makes use of the optical infrastructure in order to reduce cabling complexity while keeping the same control plane. Then, **FlaNet** Lin et al. (2012) is also a two-layer DCN architecture. Layer 1 includes a single n-port switch connecting n servers, whereas the second layer is recursively formed by n^2 one-layer FlatNet. In doing so, this architecture reduces the number of deployed links and switches by roughly $1/3$ compared to the classical three-layer FatTree topology, while keeping the same performance level. Moreover, FlatNet guarantees fault-tolerance thanks to the two-layer structure and ensures load balancing using the efficient routing protocols.

Discussion In conclusion, switch-centric architectures succeed to relatively enhance traffic load balancing. Most of these structures ensure multirouting. Nevertheless, such a design brings up in general at least three layers of switches which strongly increases cabling complexity and limits, hence, network scalability. Moreover, the commodity switches commonly deployed in these architectures do not provide fault-tolerance compared to the high-level switches.

1.1.3 Server-Centric DCN Architectures Overview

In general, these DCN architectures are conceived in a recursive way where a high-level structure is formed by several low-level structures connected in a specific manner. The key insight behind this design is to avoid the bottleneck of a single element failure and enhance network capacity.

The main server-centric DCN architectures found in the literature include **BCube**, which is a recursive server-centric architecture (Guo et al., 2009a) that makes use of on specific topological properties to ensure custom routing protocols. Another one is **DCell** which is a recursive architecture built on switches and servers with multiple network interface cards (NICs) (Guo et al., 2008b). The objective is to increase the scale of servers. Finally, **CamCube** Abu-Libdeh et al. (2010) is a free-of-switching DCN architecture, specifically modeled as a 3D DCN topology, where each server connects to exactly two servers in 3D directions, however, the suppression of the swathing by a direct connection between servers seems unfeasible.

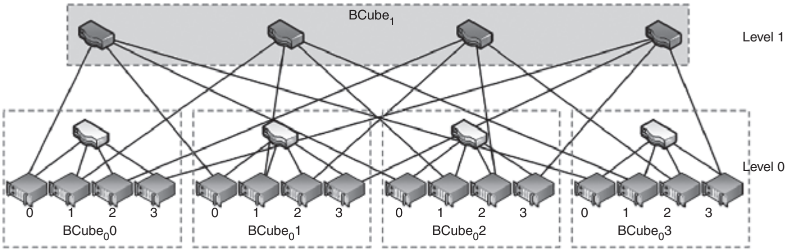

Figure 1.3 BCube$_1$ with $n = 4$.

In the following, we will cover the DCell and the BCube architectures since they represent the most cited ones.

The BCube Guo et al. (2009b) topology is a recursive architecture designed for shipping and container-based, modular data center (MDC). As depicted in Figure 1.3, the BCube solution has server devices with multiple ports (typically no more than four). Multiple layers of cheap commodity off-the-shelf miniswitches are used to connect those servers. A BCube$_0$ is composed of n servers connected to an n-port switch. A BCube$_1$ is constructed from n BCube$_0$s and n n-port switches. More generally, a BCube$_k$ ($k \geq 1$) is constructed from n BCube$_{k-1}$s and n^k n-port switches. For example, in a BCube$_k$ with n n-port switch, there are $k+1$ levels of switches. Each server has $k+1$ ports, numbered from level-0 to level-k. Hence, BCube$_k$ has $N = n^{k+1}$ servers. Each level having n^k n-port switches. The construction of a BCube$_k$ is as follows: the n BCube$_{k-1}$s are numbered from 0 to $n-1$ and the servers in each BCube$_{k-1}$ are numbered from 0 to $n^k - 1$. Then each level-k port of the ith server ($i \in [0, n^k - 1]$) in the jth BCube$_{k-1}$ ($j \in [0, n-1]$) is connected to the jth port of the ith level-k switch. The BCube construction guarantees that switches only connect to servers and never connect directly to other switches, thus multipathing between switches is impossible. It is worth noting that this kind of architecture requires virtual bridging in containers to operate. Figure 1.3 shows an example of a BCube$_1$, with $n = 4$.

Similarly to BCube, DCell Guo et al. (2008a) uses servers equipped with multiple network ports and miniswitches to construct its recursive architecture. In DCell, a server is connected to several other servers and a miniswitch. Generally, a high-level DCell is constructed from low-level DCells. The connection between different DCell networks is typically done by using virtual bridging in containers. A DCell$_k$ ($k \geq 0$) is used to denote a level-k DCell. DCell$_0$ is the building block to construct larger DCells. It has n servers and a miniswitch ($n = 4$ for DCell$_0$ in Figure 1.4). All servers in DCell$_0$ are connected to the miniswitch.

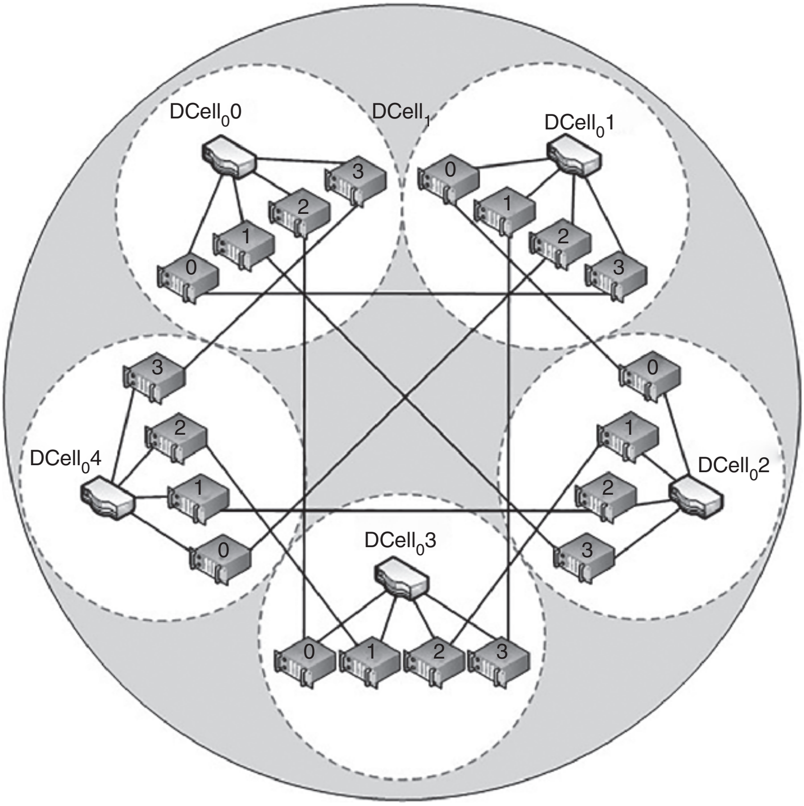

Figure 1.4 DCell$_1$ with $n = 4$.

In DCell$_1$, each DCell$_0$ is connected to all the other DCell$_0$s with one link; Figure 1.4 shows a DCell$_1$ example. DCell$_1$ has $n + 1 = 5$ DCell$_0$s. DCell connects the five DCell$_0$s as follows. It assigns each server a two-tuple $[a_1, a_0]$, where a_1 and a_0 are the level-1 and level-0 IDs, respectively. Thus, a_1 and a_0 take values from $[0, 5)$ and $[0, 4)$, respectively. Then two servers with two-tuples $[i, j - 1]$ and $[j, i]$ are connected with a link for every i and every $j > i$.

Each server has two links in DCell$_1$. One connects to its miniswitch, and hence to other nodes within its own DCell$_0$. The other connects to a server in another DCell$_0$. In DCell$_1$, each DCell$_0$, if treated as a virtual node, is fully connected with every other virtual node to form a complete graph. Moreover, since each DCell$_0$ has n inter-DCell$_0$ links, a DCell$_1$ can only have $n + 1$ DCell$_0$s, as illustrated in Figure 1.4. A DCell$_k$, is constructed in the same way to the above DCell$_1$ construction. The recursive DCell construction procedure (Guo et al., 2008a) is more complex than the BCube procedure.

To summarize, Fat-Tree topology originated in order to reduce core nodes bottleneck, by the fact that this topology grows horizontally. BCube and DCell architecture also called MDC offer the possibility of growing easily without huge change done by the administrators. Bcube can be seen as two-layer architecture with access nodes and core nodes, where the aggregation layer is dropped. DCell topology can be seen as one layer, where the access nodes play also the role of core nodes.

Server-centric DCN architectures, leading on recursive network structures, succeed to alleviate the bottleneck in core-layer switches thanks to redundant paths provided between servers. The entire DC fabric is built on servers while minimizing the set of deployed switches. Therefore, maintenance and management tasks become simpler. Moreover, network functions such as traffic aggregation, packet forwarding, etc., are delegated to servers. However, due to their recursive structure, server-centric structures significantly increase the number of servers, which would drastically increase the cabling complexity.

1.1.4 Enhanced DCN Architectures Overview

Despite the use of multi-gigabytes wired links and multiport switches in order to balance the load, the aforementioned DCN architectures are still facing flexibility and congestion challenges. Recently, a promising solution has investigated the possibility of augmenting the wired infrastructure by novel networking techniques, to enhance the capacity of DCNs. In the literature, the augmentation of such a DCN can mainly be achieved using two ways: (i) **optical** or (ii) **wireless** devices.

1.1.4.1 Optical DCN Architecture

Optical data center network (O-DCN) is a DCN architecture based on optical cabling and switching. Indeed, it has been found out that deploying such optical devices in DCs achieves a gain of 75% in IT power. First, on-demand high-speed links can be easily established thanks to the flexibility of optical network compared to the traditional wired DCN. Second, optical devices are able to ensure high bandwidth over longer ranges, and avoid, hence, the cost required for cabling along large distances. Further, O-DCNs deploy optical switches with high-radix ports, characterized by a low temperature, so as to reduce refrigeration cost. O-DCN can be classified in two main classes: (i) full optical DCN (all O-DCN) and (ii) hybrid optical DCN (hybrid O-DCN), detailed hereafter.

Full O-DCN Architectures In such architectures, all the control and data planes devices are optical. The key idea behind this full optical deployment is to provide high-speed bandwidth in the DCN. In this regard, O-DCN makes use of several techniques. First, optical circuit switching (OCS) (Chen et al., 2013) has been deployed in order to offer large bandwidth at the core layer. To do so, OCS DCN (Kachris and Tomkos, 2012) proceeds to preconfiguring the static routing paths in the switches. Second, optical packet switching (OPS), proposed in Chen et al. (2013), provides on-demand bandwidth in the DCN. In Ye et al. (2010), the datacenter optical switch (**DOS**) scalable DCN architecture has been propounded based on OPS technique. However, such an architecture suffers from low scalability. In addition, the elastic optical network (**EON**) (Talebia et al., 2014), is a kind of full O-DCN offering centralized on-demand flexibility in bandwidth switching.

Hybrid O-DCN Architectures Hybrid optical DCNs augment the wired DCNs by optical devices so that to provide extra bandwidth in an on-demand way by switching the connections in order to alleviate routing hop-counts. In doing so, hybrid O-DCNs succeed to minimize congestion effects on top of racks and to reduce traffic complexity by ensuring on-demand connections.

In this context, the authors of Chen et al. (2014) introduced a novel optical switching architecture (**OSA**) based on some techniques. Specifically, OSA makes use of a shortest path routing scheme and optical hop-to-hop switching in order to enable connectivity in DCN.

Moreover, **Helios** in Farrington et al. (2010), is a hybrid electrical–optical DCN, where each ToR is connected simultaneously to an electrical and an optical network. While electrical network is a Fat-Tree hierarchical structure, the optical one maintains a single optical connection on each ToR, with unlimited capacity. Helios deploys mirrors on a microelectro mechanical system to route the optical signals so as to alleviate traffic congestion at core level.

An additional example of hybrid O-DCN is **c-Through** Wang et al. (2010), a platform that includes a control and a data plane. The control plane measures an estimation of interrack traffic demands, then it dynamically calibrates circuits in a way that accommodates the new incoming flows. On the other side, the data plane isolates the electrical network from the optical one, and dynamically switches traffic from servers or ToRs onto the circuit or packet path. c-Through favors the use of optical paths as long as they are available, compared to the electrical routes. Nevertheless, it is worth pointing out that both of Helios and c-Through architectures fail to alleviate routing overheads.

FireFly is a wireless optical DCN architecture based on free-space optics (FSO) (Hamedazimi et al., 2014). The main advantage of such a design is that it provides a high data rate (≈ tens of Gbps) for long communication range while using low transmission power without interference. Specifically, servers in different racks communicate with each other using FSO reflected on ceiling mirrors.

Discussion In conclusion, enhancing DCN with optical technique succeed to satisfy many Cloud computing requirements. Particularly, it provides high-speed traffic with low-power consumption. Optical links alleviate the overhead compared to electric links. The aforementioned research optical approaches offer flexible switching solutions in order to make easy the bandwidth management for on-demand Cloud services. However, these designs still suffer from several limitations. First, O-DCN induces switching overhead. In fact, it requires the deployment of some modulation schemes in order to properly adjust bandwidth while switching connections, which is a challenging task. Second, O-DCN cannot be deployed in large-scale environments so far because of the high cost of optical transceivers and their long latency. Third, a significant reconfiguration latency of roughly 10 ms is induced by O-DCN which would affect applications quality of service (QoS), such as online services.

1.1.4.2 Wireless DCN Architecture

To address the challenges of both wired and optical DCN in terms of cabling complexity, deployment cost, scalability, and so on, Wireless DCN (W-DCN) has been recently explored. W-DCN architecture deploys wireless antennas, operating in the 60 GHz frequency band, to connect pairs of ToR switches. In doing so, the wired infrastructure is augmented with interrack wireless links. The main insight behind this approach is to investigate the high data transfer rate of this new emerging technique, that can reach 7 Gbps, in order to enhance DCN performance. Actually, a 60 GHz wireless link makes use of the physical beamforming technique so that the transmitted signal is concentrated in a specific direction enhancing while mitigating interference. The related wireless DCN architectures found in the literature could be classified into: (i) hybrid W-DCN and (ii) full W-DCN. Hereafter, we will detail the most relevant wireless DCN architectures.

Hybrid Wireless DCN Architectures In such an architecture, both wired and wireless infrastructures are used in the same DCN. Wireless augmentation of DCN has been first explored by the authors of Ramachandran et al. (2008)

in order to reduce cabling complexity in the wired DCN while enhancing network flexibility. The main idea behind their design is to replace some of wired bottleneck links by wireless connections operating in the 60 GHz range. Besides, Vardhan et al. (2010) designs a wireless DCN based on IEEE 802.5.3c standard (IEEE Std 802.15.3c-2009, 2009) in the wireless 60 GHz communications. To study the feasibility of such technique in DCN, the authors emulate three-tier and Fat-Tree architectures with wireless links. To do so, they propose node placement algorithms to assign nodes to racks.

Later on, **Flyway-based** DCN architecture (Greenberg et al., 2009b, Kandula et al., 2009) has been propounded in order to alleviate congestion on hotspot links in the VL2 architecture (Greenberg et al., 2009a). However, Flyway links are created on-demand in the DCN as long as there is congestion on the ToR and struggle to meet all the challenges of DCN such as scalability, high traffic load, and interference.

The authors of Cui et al. (2011c) have proposed a hybrid wired/wireless DCN architecture, where each ToR, considered as a wireless transmission unit (WTU), is equipped with a set of wireless 60 GHz radios. This hybrid architecture investigates the use of wireless infrastructure in order to reduce the congestion level of congested nodes and to handle unbalanced traffic demands in DCN.

In Cui et al. (2011a), the authors envision a hybrid Ethernet/wireless three-layered DCN architecture. Congestion on core layer is alleviated by deploying 60 GHz wireless antennas on top of racks, without needing to rearrange servers in the same rack.

To further enhance the DCN performance, some research work papers have investigated the use of beamforming technique while designing hybrid DCN architectures. Particularly, 3D beamforming has been presented in Zhang et al. (2011) and Zhou et al. (2012) in order to boost the transmission range and 60 GHz spectrum reuse in DCNs. Basically, the enhanced design sets up indirect LOS path by making use of ceiling reflectors. These enable the interconnection of wireless antennas that are not placed in the same transmission range. Typically, the horn antenna placed on each sending rack radiates the signal in some points on the reflector, and the latter transmits the signal to the receiver. In doing so, obstacles are eliminated and racks could communicate directly in one hop. While this 3D beamforming architecture significantly extends wireless coverage distance, it requires the absence of obstacles between the top of rack/container and the ceiling which is not guaranteed in real DC environments.

The authors of Katayama et al. (2011) investigate the use of steered-beam antennas in order to build a robust wireless **crossbar** switch-centric DCN architecture. In such a design, wired cabling is used only for intrarack links or to interconnect racks within the same row. On the other hand, wireless steered-beam antennas are deployed on adjacent ToRs while constituting a wireless crossbar so that cabling task is simplified and installation cost is reduced.

Angora architecture recently proposed in Zhu et al. (2014) propounds a robust wireless topology for the control plane while data is completely transiting over wired infrastructure. To do so, 3D beamforming radios are deployed on racks based on Kautz graphs, so that network latency is reduced by minimizing the path length between communicating racks. Moreover, Angora alleviates interflow interference by statically calibrating the directions of the deployed horn/array antennas. Unfortunately, the static 3D direction of antennas may strongly limits the usage of spectrum.

In Li et al. (2014), a **spherical mesh** is a wireless DCN where racks within the same transmission range are regrouped into a spherical unit. The main idea is to take profit of the geometric characteristics of the spheres to eliminate link congestion by placing antennas over them. Moreover, the spherical mesh DCN reduces the network diameter by dividing the DCN into several units.

RUSH DCN architecture is proposed in Han et al. (2015), which is a hybrid DCN based on the common three-layer tree topology. In RUSH, each ToR is equipped by only one directional 60 GHz antenna and wireless interrack links are used to minimize congestion. For that end, the authors propose a scheduling framework to jointly route flows and schedule wireless antennas.

In Cui et al. (2011b), **Diamond** DCN architecture is improved by deploying 3D wireless rings. Unlike common hybrid designs, Diamond is a hybrid wired/wireless DCN where all links between servers are wireless, whereas links connecting servers to ToRs or connecting ToRs are wired. The rings consist in regular polygons which are constructed by racks and metal reflectors, while the layers contain the servers inside racks belonging to the same level. The main reason behind the use of 3D ring reflection spaces (RRSs) is their low-cost and their ability to provide wireless links by multireflection of signals over metal. Diamond feasibility has been studied based on a real testbed.

VLCcube is a hybrid DCN architecture which is propounded in Luo et al. (2016). It is an augmented Fat-Tree structure that specifically organizes all racks into a wireless Torus structure while making use of the visible light communications (VLC) technique to generate high-speed links. In doing so, all racks are connected based on VLC links. VLC is a promising solution that guarantees low cost and important bandwidth. Moreover, VLC links do not require mechanical or electronic control.

Full Wireless DCN Architectures A completely wireless DCN architecture has been propounded in Shin et al. (2013), based on a Cayley graph, thereby named Cayley Data Center structure (**Cayley DC**). The servers are grouped into cylindrical racks. Each one is composed of five levels named stories. A story consists of 20 containers of servers. Racks are attached to densely wireless connected mesh topology with the aim of maximizing the number of active wireless links. Specifically, the Cayley DC uses wireless links not only for interrack communications but also inside racks, thanks to the mesh structure. In order to alleviate interference effects, this strategy makes use of beamforming technique with fixed-direction antennas.

Discussion To summarize, most of the relevant research work published in the recent years approves the feasibility and the efficiency of deploying 60 GHz wireless technology as an extension of conventional wired DCN architectures. Hybrid wireless/wired DCN have proven a significant capability to enhance network performance and to address the major data center issues, namely scalability, flexibility, and cabling complexity.

1.2 Comparison Between DCN Architectures

In this section, we will present a qualitative comparison between the reviewed DCN architectures while considering some specific criteria: scalability, bandwidth, cabling complexity, deployment cost, and fault tolerance. Scalability refers to the ability of the proposed architecture to easily scale and deploy more devices. Bandwidth represents the proportion of available bandwidth between servers and switches, while cabling complexity refers to the multitude of cables in the DCN induced by link redundancy. The overheads and the cost of deployment in DCN are also crucial factors that refer to the number of switches and links and their corresponding construction and deployment cost. Finally, fault-tolerance defines the ability of the designed architecture to deal with switch and link failures.

Table 1.1 illustrate a comparison between different DCN architectures based on the aforementioned aspects.

1.3 Proposed HDCN Architecture

We envision a hybrid (wireless/wired) data center network (HDCN) architecture built over a three-stage CLOS topology. Indeed, as explained

Table 1.1 Summary and analysis of DCN architectures

Architecture	Technique	Scale	Bandwidth	Scalability	Cabling complexity	Cost	Fault-tolerance
Tree-based	Wired	Small	Low	Bad	High	High	Bad
CLOS	Wired	Medium	Medium	Medium	High	High	Medium
Chen et al. (2016)							
FatTree	Wired	Medium	Medium	Medium	High	High	Medium
Al-Fares et al. (2008)							
ElasticTree	Wired	Medium	Medium	Medium	High	High	Medium
Heller et al. (2010)							
PortLand	Wired	Medium	Quite high	Medium	High	High	Good
Mysore et al. (2009)							
Diamond	Wired	Medium	High	Medium	High	Low	Medium
Sun et al. (2014)							
VL2	Wired	Large	Quite high	Medium	High	High	Medium
Greenberg et al. (2009a)							
Monsoon	Wired	Large	Quite high	Medium	High	High	Medium
Greenberg et al. (2008)							
FBFLY	Wired	Large	High	Medium	High	High	Medium
Abts et al. (2010)							
FlaNet	Wired	Large	High	Low	High	High	Medium
Lin et al. (2012)							
C-FBFLY	Wired	Large	High	Low	High	High	Medium
Csernai et al. (2015)							

DCell	Wired	Large	High	Good	High	Medium	Good
Guo et al. (2008b)							
FiConn	Wired	Large	High	Good	Medium	Medium	Good
Li et al. (2009)							
O-DCN	Optical	Small	Very high	Medium	High	High	Bad
Wang et al. (2010)							
Farrington et al. (2010)							
Hamedazimi et al. (2014)							
BCube	Wired	Small	Very high	Good	Medium	Medium	Very good
Guo et al. (2009a)							
CamCube	Wired	Large	High	Good	Very high	High	Good
Abu-Libdeh et al. (2010)							
Flyway-based	60 GHz/ Ethernet	Medium	Very high	Good	Medium	Medium	Good
Kandula et al. (2009)							
Greenberg et al. (2009b)							
Wireless Fat-Tree	60 GHz/ Ethernet	Medium	Very high	Good	Medium	Medium	Medium
Vardhan et al. (2010)							
Hybrid DCN	60 GHz/ Ethernet	Medium	Very high	Good	Medium	Medium	Medium
Cui et al. (2011c)							
Hybrid DCN	60 GHz/ Ethernet	Medium	Very high	Good	Medium	Medium	Medium
Cui et al. (2011a)							

Table 1.1 (Continued)

Architecture	Technique	Scale	Bandwidth	Scalability	Cabling complexity	Cost	Fault-tolerance
3D Beamforming	3D Beamforming	Medium	Very high	Good	Medium	High	Medium
Zhang et al. (2011)							
Zhou et al. (2012)							
Wireless crossbar	60 GHz	Medium	Very high	Good	Medium	High	Medium
Katayama et al. (2011)							
Cayley DC	60 GHz	Medium	Very high	Good	Medium	High	Good
Shin et al. (2013)							
Angora	60 GHz/ Ethernet	Medium	Very high	Good	Medium	High	Medium
Zhu et al. (2014)							
Spherical mesh	60 GHz/ Ethernet	Medium	Very high	Good	High	High	Medium
Li et al. (2014)							
RUSH	60 GHz/ Ethernet	Medium	Very high	Good	Medium	High	Medium
Han et al. (2015)							
3D Diamond	3D Beamforming/ wired	Medium	Very high	Good	Medium	High	Medium
Cui et al. (2011b)							
VLCcube	VLC	Medium	Very high	Good	Medium	High	Medium
Luo et al. (2016)							

in Section 1.1, CLOS-based architecture has been widely considered in modern DCs and has proven a high performance and resiliency.

To mimic a real data center environment, our CLOS-based HDCN architecture follows the CISCO's massively data center (MSDC) model (CISCO Systems, 2014). In fact, MSDC is a promising framework capable of supporting huge volume of traffic. To augment the wired infrastructure in HDCN by wireless links, we make use of 60 GHz wireless technology. In doing so, traffic can be forwarded over wireless and/or wired links which will alleviate the congestion load and hence improve the network performance.

In this section, we will first highlight the main properties of MSDC model. Second, we will focus on the wireless infrastructure in the HDCN by presenting the: (i) 60 GHz technology, (ii) IEEE 802.11ad standard, and (iii) deployed beamforming mechanism.

1.3.1 HDCN Architecture Based on MSDC Model

CISCO's massively scalable data center (MSDC) is a framework model that has been widely used by data center architects to build flexible DCs supporting applications distributed across thousands of servers.

Typically, MSDC is built based on a CLOS-based topology with a short spine layer serving as the aggregation switches, and a long leaf layer serving as the access layer. Specifically, a three-stage CLOS MSDC architecture using 32 port switches, and can thus connect up to 8192 servers. Based on the CISCO's MSDC reference CISCO Systems (2014), our HDCN architecture follows a three-stage CLOS topology formed by: (i) spine layer using Nexus 7000 switches and (ii) leaf layer deploying Nexus 3000 platform.

Each leaf connects to all spines. In doing so, our MSDC-based HDCN network provides multiple paths for interrack communications between servers. To leverage the multiple paths available between leaf and spine switches, MSDC data center deploys both OSPF routing and equal cost multipathing (ECMP) protocols. ECMP maximizes the load balancing of wired links' usage by dividing the traffic through multiple equal cost routes. Hereafter, we will detail the load-balancing ECMP mechanism used in our HDCN.

1.3.1.1 ECMP Protocol

ECMP (Network Working Group – Request for Comments: 2992, 2000) is the most commonly used protocol in today's data centers, for the traffic load balancing across redundant shortest routing paths. The main idea of ECMP is to divide the traffic through multiple equal cost routes. Basically, this technique is a selection tool that finds the convenient route for each transmitted packet and this by choosing the next hop from the computed OSPF routes. Mainly, two modes of load balancing are associated with ECMP: (i) per packet mode, where the packets of the same flow may have different routes and (ii) per flow mode, where the packets of the same flow are forwarded to the same next-hop, ensuring the ordered arrival of packets in transmission control protocol (TCP) mode.

In this chapter, we generate traffic, in HDCN, based on User Datagram Protocol (UDP). Consequently, based on ECMP requests for comments (RFC) (Network Working Group – Request for Comments: 2992, 2000), ECMP activates (i) the mode per-packet to maximize the load balancing and (ii) Round Robin scheduler to select the next hop (outgoing interface) for each packet.

1.3.2 60 GHz Technology in HDCN

As in prior work (Halperin et al., 2011, Kandula et al., 2009, Ramachandran et al., 2008, Shin et al., 2013), we propose in this chapter to deploy 60 GHz wireless technique in order to enhance our hybrid DCN architecture. Specifically, wireless infrastructure in our HDCN is based on IEEE 802.11ad. This standard, presented by the working group TGad as the enabler of next generation Multi-Gbps WiFi, takes advantages of available spectrum in the unlicensed 57–66 GHz band. It offers four orthogonal physical channels whose center frequencies are respectively fixed at 58.32, 60.48, 62.64, and 64.8 GHz. The capacity of each wireless channel reaches 6.7 Gbps over a short range. Consequently, the whole network of a data center can be seen as personal basic service set (PBSS). Indeed, PBSS is IEEE 802.11ad wireless LAN in which stations communicate directly with each other (i.e. ad hoc network, no need of access point) (IEEE Std 802.11ad 2012, 2012). Note that each node in PBSS is denoted by directional multi-gigabit station (DMG-STA). The latter is defined in the standard as a station operating at a frequency above 45 GHz and can support a throughput greater or equal to 1 Gbps.

In PBSS network, one DMG-STA must assume the role of controller and is denoted by PBSS control point (PCP). It ensures the QoS traffic scheduling, resource allocation, control admission, association/disassociation, etc. In other words, the PCP has a global view of nodes in PBSS. PCP is a global controller responsible for the (i) management of the Hybrid DCN and (ii) optimization of the resource usage and flows forwarding. It is worth noting that the communication between the PCP and all the DMG-STA in PBSS should be ensured over wireless network. However, some WTU deployed over DMG-STA cannot reach the PCP in wireless one-hop. In our architecture, we propose that communications between the PCP and WTUs will be supported by the wired infrastructure (e.g. Ethernet, OpenFlow). In doing so, we can see our architecture as a Software-Defined Network. In fact, the control plane is centralized in the PCP and WTUs support only the data plane (i.e. transmission of frames). IEEE 802.11ad standard defines three frame classes. In our Hybrid DCN (i.e. PBSS), we leverage the frames of Class 1. The latter contains three frame types: (i) control frames, (ii) data frames, and (iii) management frames. Concerning the control frames, we only make use of acknowledgement frames. They are transmitted over a single carrier modulation by setting the modulation and coding scheme (MCS) to 0. The latter corresponds to differential binary phase-shift keying (DBPSK) modulation, code rate is $\frac{1}{2}$, data rate is 27.5 Mbps, and receiver sensitivity is −78dBm. On the other hand, data frames are transmitted over orthogonal frequency-division multiplexing (OFDM) modulation by setting MCS to 24. The latter corresponds to 64-QAM modulation, code rate is $\frac{13}{16}$, data rate is 6756.75 Mbps (i.e. maximum data rate), and receiver sensitivity is −47dBm. Finally, the management frames are transmitted over the wired infrastructure.

Based on this specification, we propose to deploy at each ToR, a WTU composed of a set of four directional transceivers/antennas. Each transceiver is, hence, assigned to one wireless channel. Note that the four transceivers in WTU are independent, due channel orthogonality, and can be simultaneously exploited. In doing so, any rack in the data center can communicate over the wired ports (i.e. ToR) and/or using wireless channels.

It is worth pointing out that the wireless 60 GHz communication is faced with several challenges due to the free space propagation loss. The latter is due to the low-power density, and results in a short transmission range. Moreover, wireless links are prone to interfere in HDCN environment which deeply affects transmission stability. To address these limitations, we explore in this thesis beamforming technique so that to minimize the propagation loss and increase coverage distance.

1.3.3 Beamforming Technique in HDCN

The beamforming is a physical layer technique that concentrates transmission power in a specific direction (i.e. beam) so that the link rate is enhanced.

Unlike omnidirectional antennas radiating signal in a uniform way (circle), smart directional transceivers are capable of transmitting signal in one single beam (angle) by targeting only the direction of the destination. Typically, a directional antenna is in general composed by (i) an array of

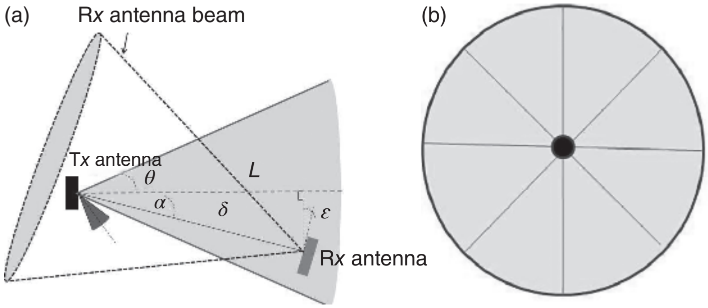

Figure 1.5 Switched-beam antenna model: (a) spherical coordinate system and (b) beams.

antenna elements (beams) and (ii) a signal processor adjusting the radiation of the latter.

Mainly, current 60 GHz beamforming antennas are available either as horn antennas (Halperin et al., 2011), phased-array antennas, or switched-beam antennas (Zhu et al., 2014). While the phased-array transceivers are steerable devices that appropriately steer each beam at the desired target direction, horn antennas are in general used for fixed links, in long-range outdoor environments. Recent researches Zhu et al. (2014), Zhou et al. (2012) claim that both array and horn antennas require a mechanical rotation mechanism at each single communication to adjust the beam direction. This frequent antenna rotation induces an extra delay estimated to equal 50 ns for array antennas and to range from 0.01 to 1 second for horn antennae (Zhou et al., 2012). Based on these observations and as recommended by Zhu et al. (2014), we deploy, in this thesis, switched beam antennas to avoid performance degradation. In fact, such devices have been considered to be less complex than the other smart radios and are cheaply implemented. As depicted in Figure 1.5b, a switched beam antennae is characterized by an array of N beams (i.e. sectors). Each one covers an angle of $2\Pi/N$. Accordingly, the transmitting antenna switches to (i.e. selects) the beam achieving the highest gain while covering the destination. The receiving antenna senses the signal on all the sectors and exploits only the one achieving the maximum gain. The signal coming from potential interfering antennas is either not received or significantly weak.

We assume the geometric signal propagation model (Shin et al., 2013) based on a spherical coordinate system with origin the transmitting antenna as shown in Figure 1.5a. The receiver antenna is characterized by radius δ, azimuth θ as shown in Figure 1.5a. Note that we assume 2D beamforming and hence elevation is equal to 0.

Our HDCN architecture is illustrated in Figure 1.6.

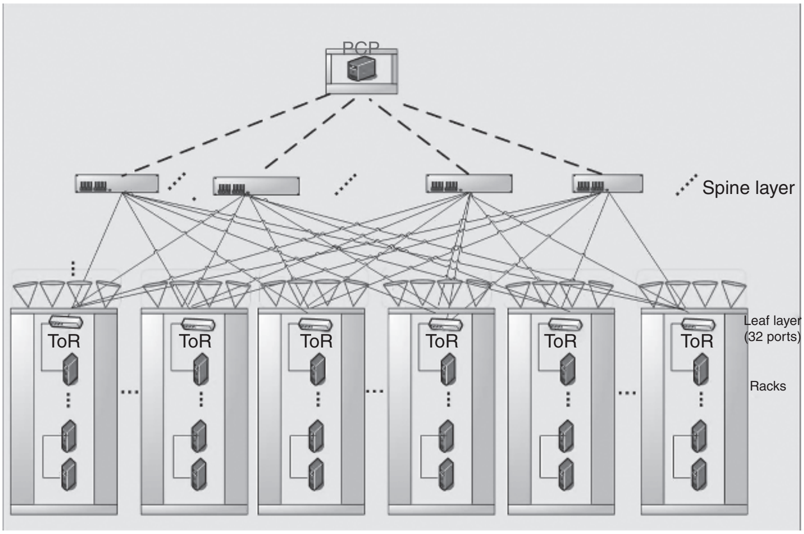

Figure 1.6 Hybrid CISCO MSDC architecture of a DCN.

1.4 Conclusion

In this chapter, we provided an overview of DCN architectures. First, we proposed a taxonomy classifying the relevant DCN structures into three main classes: (i) switch-centric, (ii) server-centric, and (iii) enhanced DCN architectures. We deeply analyzed the key properties of each class. Afterward, we provided a qualitative comparison study between the different DCN architectures. Finally, we presented our chosen hybrid DCN architecture based on (i) Cisco's MSDC framework and (ii) wireless 60 GHz technique. In the next chapter, we will present a detailed review on the most relevant research strategies in the literature tackling wireless/wired resource allocation problem for both one-hop and multihop communications in HDCN.

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