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The features, hardware, and architectures of data center networks: A survey

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HIGHLIGHTS

- We give a survey on the features and hardware of Data Center Networks.
- We thoroughly analyze the topology designs and architectures of DCNs.
- We provide both qualitative and quantitative analyses on the features of DCNs.

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ABSTRACT

The rapid development of cloud computing in recent years has deeply affected our lifestyles. As core infrastructures of cloud computing, data centers have gained widespread attention from both the academia and industry. In a data center, the data center network (DCN) that plays a key role in computing and communication has attracted extensive interest from researchers. In this survey, we discuss the features, hardware, and architectures of DCN's, including their logical topological connections and physical component categorizations. We first give an overview of production data centers. Next, we introduce the hardware of DCN's, including switches, servers, storage devices, racks, and cables used in industries, which are highly essential for designing DCN architectures. And then we thoroughly analyze the topology designs and architectures of DCN's from various aspects, such as connection types, wiring layouts, interconnection facilities, and network characteristics based on the latest literature. Finally, the facility settings and maintenance issues for data centers that are important in the performance and the efficiency of DCN's are also briefly discussed. Specifically and importantly, we provide both qualitative and quantitative analyses on the features of DCN's, including performance comparisons among typical topology designs, connectivity discussion on average degree, bandwidth calculation, and diameter estimation, as well as the capacity enhancement of DCN's with wireless antennae and optical devices. The discussion of our survey can be referred as an overview of the ongoing research in the related area. We also present new observations and research trends for DCN's.

1. Introduction

The term "cloud computing" in the modern sense appeared in a Compaq internal document as early as 1996 [143]. In 2006, Google CEO came up with the concept of "cloud computing" in business [147], which is a model based on the premise that the data services and architecture should be on "cloud" servers. Having the right kind of browser or software in a device (e.g., PC, mobile phone, etc.), you can access to the cloud services freely. Also in 2006, Amazon introduced the Elastic Compute Cloud (Amazon EC2), which is a web service that provides resizable compute capacity in the cloud [7]. In Wikipedia, the term "cloud computing" involves the provision of dynamically scalable and often virtualized resources as a service over the Internet. In science, cloud computing is synonymous to distributed computing over a network, which means the ability to run a program or application simultaneously on many interconnected computers [174]. Generally, cloud computing is a service model where tenants can acquire resources on demand based on service-level agreements (SLAs). Depending on the level of resources, cloud service models can be categorized into Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Software-as-a-Service (SaaS), and Anything-as-a-Service (XaaS, X can stand for network, database,

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communication, etc.). Data-Center-as-a-Service (DCaaS) is also an important cloud service mode. Data center providers offer places and customized guidances for tenants to construct their data centers with their own equipments. Among these cloud service models, IaaS is the most basic one where providers offer computers (physical or virtual machines) and other resources placed in (part of) a building known as a "data center".

Although the concept of "data center" was proposed in the 1990s, the characteristic features and requirements of a data center actually appeared at the beginning of the very first computer operation [17]. In the early 1960s, the lowest-level (i.e., Tier 1) data center had been deployed, probably a computing center of some laboratory in a university [164]. Nearly 30 years after, in the mid-1990s, the highest-level (i.e., Tier 4) data center was constructed. The name "data center" was used when the Tier 4 data center was developed. Telecommunications Infrastructure Standard for Data Centers (i.e., ANSI/TIA-942-2005) defines data center as: a building or portion of a building whose primary function is to house a computer room and its support areas [161]. Google defines a data center as a building where multiple servers and communication equipment are co-located because of their common environmental requirements and physical security needs, and for ease of maintenance [19]. Based on the two definitions, the computer room is the core physical environment of a data center, which consists of computing equipments for data processing and other areas offering support services to the computer room. Support services mainly comprise the power supply system (including backup power system), cooling system, lighting system, cabling system, fire protection system, and security system. In spite of these highly automated support systems, the staff is also essential to handle routine work and emergencies.

Data centers are the main infrastructures to support many applications, such as cloud service, supercomputing, and social networks. A data center is a huge building consisting of various areas, among which the data center network (DCN) plays a pivotal role in computing and communication. DCN connects the physical components of data centers (e.g., servers, switches) in a specific topology with cables and optical fibers, and the efficiency and performance of a data center greatly depend on the DCN. Since SIGCOMM (the flagship conference of the ACM Special Interest Group on Data Communication) first set a session on data center networking in 2008, the architecture design has become a very active research field to improve the efficiency and performance of DCN's. Many novel architectures have been designed and presented, and many novel devices have been attached to DCN's, such as wireless antennas and optical switches. In just a few years, several surveys on DCN's have been presented. However, all these surveys are not comprehensive, and the limitations include the following four aspects:

1. These surveys hardly include any introduction and discussion on the hardware in DCN's, such as switches, servers, storage devices, racks and cables, which are highly essential for designing DCN architectures. Making these information available provides a benefit for the research communities to understand the DCN's thoroughly.
2. Although several surveys presented some simplified and partial quantitative analyses on the performance of DCN architectures, comprehensive quantitative analyses are scarce, which are more helpful for the researchers to understand DCN's in depth.
3. These surveys only discussed several aspects of DCN's without an overall perspective. A comprehensive survey will benefit the researchers in future.
4. These surveys focused almost exclusively on the wired architectures of DCN's, whereas wireless and optical architectures are hardly proposed.

In this paper, we comprehensively focus on the features, hardware, and architectures of DCN's, including their logical topological connections and physical components categorizations. We first give an overview of production data centers. Next, we introduce the hardware of DCN's, including switches, servers, storage devices, racks and cables used in industries, which are highly essential for designing DCN architectures. And then we thoroughly analyze the topology designs and architectures of DCN's from various aspects, such as connection types, wiring layouts, interconnection facilities, and network characteristics based on the latest literature. Finally, the facility settings and maintenance issues for data centers are also briefly discussed.

Specifically and importantly, we provide both qualitative and quantitative analyses on the features of DCN's, including performance comparisons among typical topology designs, connectivity discussion on average degree, bandwidth calculation, and diameter estimation, as well as the capacity enhancement of DCN's with wireless antennae and optical devices. Our survey can be referred as an overview of the ongoing research in the related area. We also present new observations and research trends.

The rest of this paper is organized as follows. Section 2 provides an overview of production data centers. Section 3 introduces the hardware of DCN's used in industries. Section 4 summarizes the architectures of DCN's, then offers the comparisons and future research directions. Section 5 introduces the considerations of the support systems of DCN's. Section 6 concludes the survey.

2. An overview of production data centers

Nowadays, production data centers (DC's) have become indispensable for large IT companies. An overview can provide a benefit for the research communities to better understand production DC's comprehensively. In this section, we first introduce several representative production DC's, then focus on their main features, including size, infrastructure tiers, and modularity. Finally, we introduce green DC's as the new trend.

2.1. Representative production data centers

Large IT companies constructed several production DC's to support their business. Others are rented out to provide services to medium-sized and small-sized enterprises that cannot afford their own DC's.

Google owns 36 production DC's globally, 19 of which are in America, 12 in Europe, 3 in Asia, 1 in Russia, and 1 in South America, as shown in Fig. 1(a) [148]. These DC's support Google services, such as searching, Gmail, and Google Maps. In 2016–2017, Google DC's will be constructed in Oregon USA, Tokyo Japan and other ten countries and regions.

The prototype of Google's first DC in Fig. 1(b), *BackRub* was once located in the dorm of Larry Page (one of Google's founders) [58]. Although it was simple and crude, BackRub had met basic requirements of Google searching at that time.

Google cost nearly $600 million to build the first DC in 2006, say, Portland Dalles Data Center. It is a pair of 94,000-square-foot DC's that sit on the banks of Columbia River, and is powered by the Dalles Dam [13]. Two four-story cooling towers are used to low the water temperature, and the water vapor is shown in Fig. 1(c) [59]. Google announced another $600 million to build a new DC with 164,000 square feet in Dalles in 2013, and opened it in 2015 [101].

Another Google's typical DC is Georgia Douglas County Data Center, as shown in Fig. 1(d). It provides services for the key business such as searching, Gmail, Maps [59]. Finland Hamina Data Center is reconstructed from a paper mill, which utilizes sea water along pipelines of the paper mill to control the data center temperature, as shown in Fig. 1(e) [59].