Research on Key Energy-Saving Technologies in Green Data Centers

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***Abstract*—With the rapid development of the data-intensive industries, the demands for large-scale data centers become tremendous. Accordingly, the problem of saving energy in the operation & maintenance of the data centers has become increasingly important. In this paper, we summarize the key technologies for networking energy saving and environment energy saving in large-scale data center networks. The key technologies include network topology optimization, network routing optimization, flow scheduling, and intelligent electric management and optimization of data centers. The network energy consumption with different network topology structures and routing algorithms are analyzed and compared, and important technical directions for several energy saving mechanisms such as energy-efficient routing and network device sleeping technology on network energy saving of the entire data center are studied. Besides, other research directions of relevant energy saving and cost reduction technologies are studied in the paper. (*Abstract*)**

***Keywords*—Data center network, energy-efficient routing, flow scheduling, game theory (*Keywords*)**

I. INTRODUCTION

Big data[1], as set of data, is now a critical asset for society and an essential productive factor, and currently has been applied in many industries including telecommunications, entertainment, health care, administration affairs and retail. The big data technologies refer to data collection, storage, screening, analysis, forecast, and results presentation. The data centers[2], as the carrier of big data, provide many Internet platform services to users, including basic services and a variety of value-added services. Data centers include several subsystems such as power systems, HVAC systems, and weak electricity systems to guarantee the stability and availability of the big data centers.

With the rapid development of new-generation information technologies such as artificial intelligence and Internet of Things, the volume of data collected from devices will explode, and large-scale data will be sent to the cloud. Thus, higher standart is required for the data centers, the data center industry is developing very fast worldwide, and more super-large scale data centers will be built. In data centers, thousands of servers and other devices run continuously and comsume energy significantly. It is shown that, in 2017, the total energy consumption of the data centers in China reached 12 TWh, exceeding the total generating capacity of the Three Gorges Dam. However, there is great potential for optimizing energy consumption in data centers. For example, the overall energy utilization is very low in low-load network topology [3], leading to huge waste of networking resources and power and to high electricity costs. Also, the placement and parameter configuration of air conditioners in data centers are also important for energy saving. Currently, energy consumption problem holds back the rapid development of the data center network and causes severe problems in energy management and environmental pollution. Therefore, how to build green data centers[4] has became a key issur and received extensive attentions. Governments and industries highly value gree data center technologies to reduce operation and management costs and to achieve goals of energy saving and sustainable development [5].

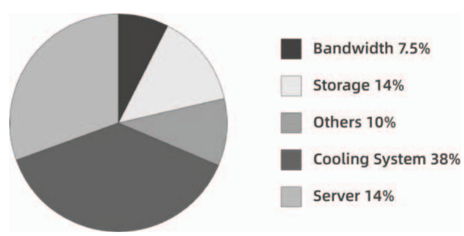

Figure 1 Energy Distribution of Data Center

As shown in Figure 1, the energy consumption devices in data centers can be generally classified into three categories: (1) terminal devices, such as server, memory and individual host; (2) network devices in wired and wireless networks, such as router and switch; (3) basic environment devices, such as cooling, lighting, and power supply devices. With the development of technologies, energy consumption reduction technologies for terminal device is relatively mature, and industry standards have been made and products

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have been produced. Energy saving mechanisms for environment devices such as refrigeraters and lightings in data centers is not the topic in this paper. This paper focuses on the management of environment energy efficiency .

Switches [6] and servers [7] are the core components of data center network. A key technology to build a green data center is to optimize servers and network routing. In this paper, the current system architecture and operation methods of data centers are analyzed, and the energy saving mechanism and how to build a green energy-saving data center network are studied. Through comparative analysis on energy efficiency of the data center network, the key influence factors are identified to achieve energy saving and consumption reduction for network device as a single unit with heavy networking load. Current network energy-efficient routing mechanisms are studied in order to reduce resource consumption in data centers while assuring certain network throughput.

The research results in this paper is of great significance for reducing energy consumption in data centers and building a green, energy-saving, and environment-friendly data center.

II. Overview of Network Energy-Saving Technologies

With the rapid development of Internet and network performance improvement in recent years, the energy consumption control problem of the network devices has become increasingly severe, and has begun to attract extensive attention inside and outside the Internet industry. Therefore, the energy-saving technologies for network devices have become one of the key points in research works.

A. Device-level energy saving technology

Energy consumption reduction for a individual device is of great significance to the research on energy consumption reduction for data centers. When the network devices are in an idle state, the simplest energy saving method is to directly shut down the devices. However, due to the existence of huge number of data center devices, it will take a long time to restart the devices from shutdown, normal network services interrupted, and high additional costs incurred. Therefore, the "sleeping" mode is added between device shutdown mode and restart mode, and can be switched automatically and freely according to tasks to be processed, so as to reduce wastes and improve overall energy utilization, which is an effective method to reduce power consumption.

Specificly in device sleeping technology [8], high efficiency sleeping strategy attracts the most attention. The sleeping strategy determines the number and frequency of switches between the working state and the sleeping state, and thus affecting the quality of the entire energy consumption management system and network services. Currently, three technologies are applied to ensure that the network device sleeping strategy is reasonable and efficient. They are based on timer technology [9], message wake-up technology, and proxy technology respectively.

The timer sleeping technology is mainly applied to control the device sleeping time by setting a timing mechanism. Before the sleeping mode of the device is enabled, a timing mechanism is set to control the time; before the time ends, the equipment is in the sleeping state, and no information is processed. The message wake-up technology mainly refers to installation of message perception hardware in network devices (generally in input interfaces). When information is perceived by hardware, the device is immediately awakened for message processing so as to avoid message loss and delay caused by long sleep. However, there is a variety of messages for periodic interaction in reality, which can not be fully processed by the two methods mentioned above. So the energy saving performace is limited. In subsequent researches, Gunaratne et al. found that not all periodic messages in the network needed to be processed, most of which can be ignored. They used proxy devices to process messages, resulting in a third way of network device sleeping technology using proxy.

Device-level energy-saving technologies are classified into three categories based on the realization method and complexity: device sleeping technology, dynamic adaptation technology, and new hardware design technology. The device sleeping technology and dynamic adaptation technology are mainly applied for lightweight [10] upgrade and optimization of devices in the existing networks, thereby reducing the energy consumption in data center network. For the new hardware design technology, the energy utilization efficiency is mainly improved by reconstructing the network equipment system. These three technologies have their own advantages & disadvantages and applicable scenarios.

For the dynamic adaptation technology [11], the network energy utilization effciency is mainly improved by dynamically adjusting network resources according to user demands and the real-time network load.

With new hardware design technology, the architecture of the existing network equipment is redesigned and adjusted, so as to achieve energy saving and consumption reduction in data center networks. Compared with device-level energy-saving technology and dynamic adaptation technology, it is relatively more expensive and requires more efforts to realize the new hardware design technology, but can abtain better energy-saving performance.

B. Network-level energy saving technology

In the research on the network-level energy-saving technology, we shall pay attention to how it can be adapted to the existing routing protocols in the network and shall notice the negative effects resulted from the energy-saving effects. The core of energy saving and consumption reduction in data center network is to calculate and configure energy-efficient routes based on real-time network load, and to reduce network energy consumption through resource scheduling.

The core of the research on the network-level energy-saving technology is to reduce energy consumption in the entire network with coordination and cooperation of the entire network devices. If this technology is applied, the energy-efficient routing protocols are the focus of technical research. The energy-efficient routing protocols vary with the network size. In WAN [12], research focuses on energy-efficient routing technology. Fewer resources are used to provide services in the Internet autonomous system, and the network service quality is guaranteed at the time of reducing energy consumption. In LAN, research focuses on the energy-efficient routing of data center. Although intra-domain energy-efficient routing [13] contributes to network energy reduction, the compatibility of network routing protocols needs to be considered. The energy-efficient routing of data center network features strong flow control and flexible resources allocation, which can enhance network performance and reliability. For energy-efficient routing in data center network, with real-time analysis on network load, the energy-efficient routes are automatically calculated and configured, and idle network resources are put into sleeping state, thereby reducing overall network energy consumption.

The network-level energy-saving technology also includes energy-saving mechanisms of the application layer and transport layer [14]. The energy efficiency in data center network can be improved through combined usage of these methods.

III. Energy Saving of Data Center Network

A. *Energy-efficient routing mechanism based on reliable network throughput*

With large-scale construction and development of data centers, network bandwidth has become a bottleneck which restraints data-intensive distributed applications. The transmission speed of the network is determined by bandwidth resources. On account of the application scenarios that are limited by bandwidth, an energy-efficient routing mechanism with reliable network throughput is proposed to break the restraints on network throughput and network reliability. The energy-efficient routing mechanism keeps idle resources in sleeping state by deleting some network links and switches according to certain energy saving strategies, so as to achieve energy saving and consumption reduction in data center network [15]. The energy-efficient routing of the data center network can run independently during computing, and does not rely on the routing protocols in the existing network.

B. *Energy saving mechanism based on the combination of routing and flow preemptive scheduling*

Currently, most energy-saving routing solutions focus on only energy-efficient transmission routes, while the scheduling strategies are not taken into consideration. However, considering more data exists, the energy saving and consumption reduction in data center network can be achieved in a more flexible and effective way by combining with the network flow scheduling strategy.

[15] According to the strategy of combining with network scheduling, an energy saving mechanism which combines routing with flow preemptive scheduling - FPPAR (flow preemption and power-aware routing) is proposed. The flow preemptive scheduling means that scheduling is provided based on priority, and network resources are scheduled by preemption, so that bandwidth resources can be exclusively used during transmission, thereby effectively improving the utilization efficiency of network resources.

The FPPAR mechanism is an energy-saving and consumption-reduction algorithm that combines routing with flow preemptive scheduling, and is based on basic idea that network flow is scheduled by a preemption method which is selected based on priority [16]; an energy-efficient transmission route can be selected for the network flow, so as to fully improve the utilization efficiency of switches. The FPPAR mechanism defines two transmission routes: idle route and preemption route. The network flow is efficiently calculated using these two routes so as to optimize the transmission route resources [17], to achieve energy saving and consumption reduction in data center network, and to improve resource utilization efficiency.

C. *Dynamic flow scheduling based on game theory*

The above two energy-saving technologies focus on energy saving. However, with the continuous emergence of new applications, the users will continuously put forward new requirements on service quality. The emphasis is put not only on energy consumption of the data centers, but also on how to balance the service quality of the data centers while saving energy [18].

The balance between energy saving & consumption reduction and service quality can be reached based on game theory. Based on game theory[19], the demand balance of data center network transmission is found out, and network resources are dynamically scheduled, so as to reduce the energy consumption of data center network while guaranteeing the service quality.

IV. Environmental Energy Saving of Data Center

A. *Intelligent energy efficiency management*

During daily operation and maintenance of data centers, the energy consumption of the sub-systems of data centers is monitored and managed so as to find out the keys of the energy efficiency problems and to take effective management measures.

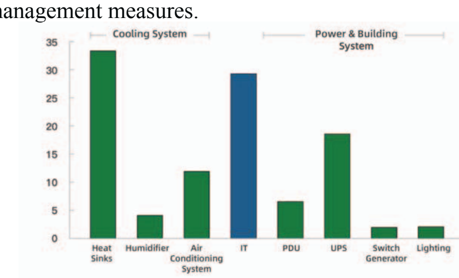

Figure 2 Electricity Consumption Ratio of Systems of Data Centers

For intelligent energy efficiency management, environment big data shall also be fully used, and energy efficiency management is further provided based on the data-driven method (collection of massive data by sensors; introduction of weather, equipment model, etc.). After data cleaning, the data rules are analyzed through machine learning so as to forecast future setup of the equipment parameters and achieve energy saving[20].

1) *Real-time energy consumption monitoring*

Real-time and all-round monitoring is provided for the electricity consumption of the systems of the data center, such as IT equipment, air-conditioning equipment, lighting equipment and power equipment, and detailed statistics and analysis are given on the electricity consumption of the equipment. An alarm is sent in case of any electricity consumption abnormality, and adjustment recommendations are given; multiple data information reports are generated at fixed time, as a stronger basis for decision making by the managers [21].

2) *Real-time PUE monitoring*

The capacity, IT load, equipment power, cooling system and other systems of the data center network are subdivided, and the system data are continuously collected at regular intervals (15 minutes) to calculate single PUE value. The continuous measurement values are used to analyze the changes of PUE under different time and different variables (such as weather conditions, IT load and cooling equipment performance) and find out the management rules for energy saving and efficient operation of the data center, and improve the work efficiency of data center managers [22].

3) Real-time environment monitoring

The real-time environmental indicators are embedded in the energy efficiency management platform, and the temperature field and humidity field distribution in the data center computer room are presented in a visual (2D/3D) way, and various areas of the data center are controlled according to the energy saving standards.

B. Airflow simulation and optimization design

The airflow of the data center significantly affects the overall temperature field [23]. Unreasonable airflow design will lead to low cooling efficiency of the air conditioners and affect the configuration and energy consumption of the air conditioners.

The data center is designed to build a model for and optimize the airflow in the computer room of the data center according to the selection design scheme of the refrigeration air conditioner, so as to solve the heat imbalance caused by airflow turbulence, short circuit and wind power imbalance inside the computer rooms. More reasonable airflow layout designs are given to reduce the equipment power and minimize the operation energy consumption. Specific steps are as follows.

a) Establish a 3D solid model of the computer room and a 3D flow mathematical model of the confined space, and calculate the internal flow field pressure and velocity field under different working conditions.

b) Carry out 3D two-phase flow field numerical simulation, calculate the motion trajectory of solid particles, analyze the effects of the air conditioner inlet and outlet on the uniformity of the flow field, and solve the potential problems such as uneven indoor air distribution and heat dissipation difficulty, thereby reducing energy consumption.

c) Optimize the design of the indoor flow field plan for the computer room (for example, optimize the inlet and outlet designs; adjust the position of the unit, and increase the deflector), improve the internal space flow characteristics, and increase the working efficiency of the indoor equipment.

C. Energy forecast and trading

On the part of the construction and operation companies, electricity saving not only includes reduction of actual electricity consumption through technical improvements, but also includes actual reduction in electricity costs under constant electricity consumption through energy trading, etc. (Strictly speaking, this section is not included into environmental energy saving, but into operation and maintenance management. For the sake of convenience, this section is put here).

1) Electricity trading

The electricity costs are the main costs for daily operation of the data center. According to the statistics, the electricity costs account for 60% of the costs for daily operation of the data centers. Electricity consumed by the data centers is purchased from the electricity market, so the data centers can benefit from a more preferential electricity price, and the electricity costs are directly reduced by nearly 20% [24].

Electricity consumed by the data center is classified into large industrial power supply, and the specific electricity price varies slightly with different voltage levels, with an average price of about RMB 0.6/kWh. In terms of price, the electricity price of the power generation enterprises is about RMB 0.3/kWh, and the sum of the on-grid electricity price and capacity electricity price is about RMB 0.2 /kWh, totaling to about RMB 0.5 /kWh to be finally paid by the users. The difference between the industrial electricity price and the electricity market price is about RMB 0.1/kWh, with a considerable discount.

2) Power load forecast

In the electricity spot market, the contracting strategies, quotation strategies, trading strategies, and user economic calculations are based on power load forecast. Therefore, power load forecast and the accuracy of the forecast results are crucial to reduce the operating costs of the data centers. The neural network load forecast algorithm can be used to forecast short-term (more than one day but less than two weeks) and ultra-short-term (within one day) power load on the user side, and previous data are used as training samples. Relevant algorithms are used for network training until the forecast accuracy meets the requirements. This neural network is used as a power load forecast model.

V. CONCLUSION

In recent years, relevant services of the data-intensive industries have higher requirements on the bandwidth and reliability of the data center network, and many new network architectures have emerged, but with huge network energy consumption and low energy utilization rate [25]. In this paper, specific to the green energy saving problem of the data center, the research started with network energy saving and environmental energy saving, of which network energy saving started with network topology, network routing, and flow scheduling. Network energy consumption under different architectures was analyzed and compared, and the energy-efficient routing, energy-saving mechanism, network equipment sleep technology and others provided an important technical research direction for the network energy saving of the entire data center. Environmental energy conservation of the data center started with energy efficiency management, environmental monitoring, flow field optimization, and energy trading, and every effort is made to find out the research directions of the energy saving and cost reduction technologies.

The next key research directions include:

Firstly, designing and implementing network energy-efficient routing mechanism on the premise of guaranteeing network efficiency. In the process of building a green data center, it is crucial to achieve energy saving and consumption reduction of IT software and hardware systems. At present, researches on software & hardware technologies and energy-saving technologies are prommoted in various industries. Through comparative analysis on energy consumption in data center network, the key influence factors will be found out to achieve energy saving and consumption reduction in a single network device under large network fluctuations. Besides, plans will be developed at the stage of designing network plans and protocols, an energy-efficient network routing mechanism will be designed with certain network throughput so as to reduce network energy consumption.

Secondly, the energy saving mechanism based on combination of routing and flow preemptive scheduling will be studied. The exclusive transmission links will be used to effectively reduce the network energy consumption and the average completion time of the network flow, to improve the utilization rate of network links and energy, and to reduce the energy consumption in network data center.

Thirdly, the dynamic flow scheduling based on game theory will be proposed to maintain the balance between energy saving and service quality of the data center network and to maximize the effect.

Finally, through environment monitoring and big data analysis, the problem of accurate energy efficiency management will be solved, thereby improving the environment energy saving indexes.

The above research will be of great significance to build a green energy-saving data center, thus boosting the development of energy saving, emission reduction, and innovation in big data industy.

ACKNOWLEDGMENT *(Heading 5)*

The preferred spelling of the word "acknowledgment" in America is without an "e" after the "g". Avoid the stilted expression "one of us (R. B. G.) thanks ...". Instead, try "R. B. G. thanks...". Put sponsor acknowledgments in the unnumbered footnote on the first page.

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