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Green data center with IoT sensing and cloud-assisted smart temperature control system

Qiang Liu[a], Yujun Ma[b], Musaed Alhussein[c], Yin Zhang[d,*], Limei Peng[e]

[a] School of Computer and Information Technology, Beijing Jiaotong University, Beijing 100044, China
[b] Computer Network Center, Nanyang Institute of Technology, Nanyang 473004, China
[c] Computer Engineering Department, King Saud University, P.O. Box 51178, Riyadh, Saudi Arabia
[d] School of Information and Safety Engineering, Zhongnan University of Economics and Law, Wuhan, China
[e] Department of Industrial Engineering, Ajou University, South Korea

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ABSTRACT

With the growing shortage of energy around the world, energy efficiency is one of the most important considerations for a data center. In this paper, we propose a green data center air conditioning system assisted by cloud techniques, which consists of two subsystems: a data center air conditioning system and a cloud management platform. The data center air conditioning system includes environment monitoring, air conditioning, ventilation and temperature control, whereas the cloud platform provides data storage and analysis to support upper-layer applications. Moreover, the detailed design and implementation are presented, including the dispatch algorithm for the temperature control, topological structure of the sensor network, and framework for the environment monitoring node. A feasibility evaluation is used to verify that the proposed system can significantly reduce the data center energy consumption without degradation in the cooling performance.

1. Introduction

In recent years, the Internet of Things (IoT), cloud computing and Big Data techniques have made remarkable progress in information technology. These techniques have become an important engine of economic growth around the world [1–5]. Furthermore, with the rapid growth of mobile networks [6,7], the number of various devices connected to the Internet is increasing, and the explosion of data generated by these devices has led to exponentially increasing requirements of computing and storage capacity [8,9]. The booming Big Data industry accelerates the development of technological evolution and application innovation. Currently, governments have realized that Big Data plays an important role in economic development, public services, national security, etc. As the core infrastructure of Big Data, the Data Center (DC) is becoming more significant [10].

The DC is a complex infrastructure, which includes not only computing, networking and storage systems but also redundant data communication systems, environmental control equipment, and safety supporting devices [11]. The DC plays a critical role in ensuring the continuity of Information Technology (IT) infrastructure and providing necessary guarantees for information security [12]. Fig. 1 illustrates a practical DC in an Internet Service Provider (ISP) consisting of power, cooling, fire protection, security and other subsystems.

To maximize energy efficiency and minimize environmental impacts, the green DC has been proposed in recent years, which is regarded as the inevitable development trend of DCs [13]. High efficiency is the primary concern of green DCs, which mainly refers to the power supply of IT devices and air conditioning systems [14]. To reduce the power

* Corresponding author. Tel.: +8618086626321.
E-mail addresses: liuq@bjtu.edu.cn (Q. Liu), yujun.hust@gmail.com (Y. Ma), musaed@ccis.ksu.edu.sa (M. Alhussein), yinzhang@znufe.edu.cn (Y. Zhang), auroraplm@ajou.ac.kr (L. Peng).

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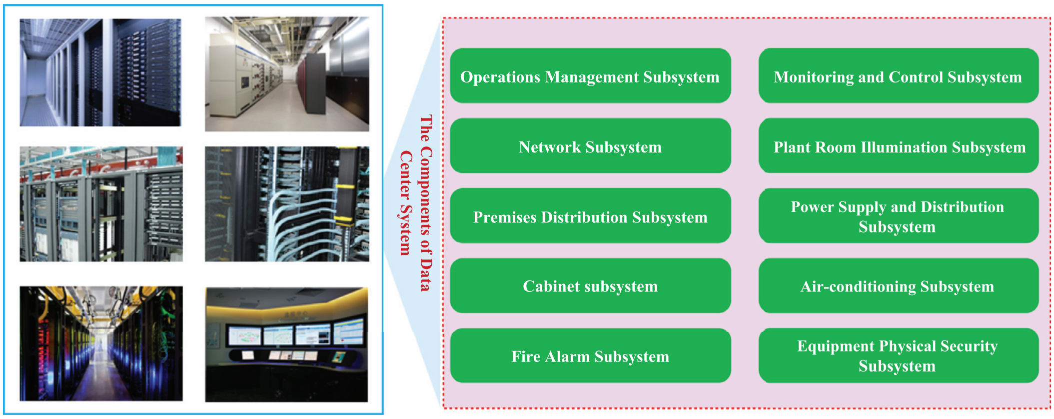

Fig. 1. A practical data center system in an ISP.

consumption of IT devices, various novel and efficient proposals have been successfully deployed, such as virtualization and cloud computing [15,16]. Moreover, the energy consumption of air conditioners is expected to be reduced by establishing a low-temperature zone, deploying ventilation and water-cooling systems, etc. Unfortunately, these solutions have limitations in terms of economy and maintainability.

To address the aforementioned challenges, we propose a cloud-based air conditioning system for green DCs. Specifically, this paper makes the following contributions: 1) We propose a cloud-based approach to effectively reduce DC power consumption through a slight update and simplify and standardize the management of the cooling system. 2) We propose a multilevel intelligent temperature control algorithm to increase the energy efficiency of the cooling system. 3) We deploy the proposed scheme on a small DC to prove that the energy efficiency has been significantly improved.

The remainder of this article is organized as follows. Section 2 presents related works on the DC. In Section 3, we introduce the proposed system architecture for the DC temperature control system. Section 4 describes the proposed system design and implementation, and Section 5 illustrates the performance evaluation of the proposal based on actual experiments. Finally, we conclude this article in Section 6.

2. Related work

The evolution of the DC has included the following three main stages [17]:

(1) **Distributed DCs**: With the continuous improvement of business, the enterprises must establish DCs in different regions according to the information demand of subsidiaries. However, with the increasing demand for data management and services, distributed DCs fail to address data sharing and business continuity.
(2) **Centralized DCs**: To improve the quality of information services, reduce management complexity and integrate business data and applications, the originally distributed servers, storage devices and other IT-related devices are centrally managed. Moreover, centralized DCs provide unified security management and disaster recovery.
(3) **Cloud-enabled DCs**: Assisted by advanced cloud computing and virtualization techniques, DCs can flexibly meet the dynamic business demand and efficiently reduce energy consumption [18]. Meanwhile, because of the energy crisis [19], cloud-enabled DCs with considerable performance in energy savings have become a preferred approach to establishing green DCs [11].

Therefore, many studies attempt to use cloud-enabled techniques to reduce energy consumption on the premise of guaranteeing Quality of Service (QoS) and Quality of Experience (QoE) [20–23]. In [24], Kashif et al. proposed a novel green DC architecture to provide comprehensive monitoring and live migration and optimization of virtual machines. In [25], Jetsadaporn and Chawalit designed a simulation system to simulate DC cooling systems to provide guidance for reducing energy consumption.

Although the existing approaches are able to reduce DC energy consumption, they require massive capital investment and are difficult to deploy in a practical DC. Hence, we propose a smart multilevel temperature control system for green DCs to address these challenges.

3. Cloud-assisted smart temperature control system architecture

A stable and reliable temperature control system is one of the most important parts of a DC; therefore, the air conditioning and refrigeration system is an important consideration during the design phase. For example, many large DCs have invested significant capital to build a stable, reliable and advanced energy-saving air conditioning system. However, because of a limited budget, some small and medium DCs must install inexpensive household air conditioning ventilation systems, which incur significant potential risks and trouble for the DC operation and maintenance.

Hence, based on our comprehensive investigation of the existing solutions for DC air temperature control systems, we propose a cloud-assisted smart approach to control temperature in DCs. The system architecture is shown in Fig. 2, which is available for implementation in a practical DC.

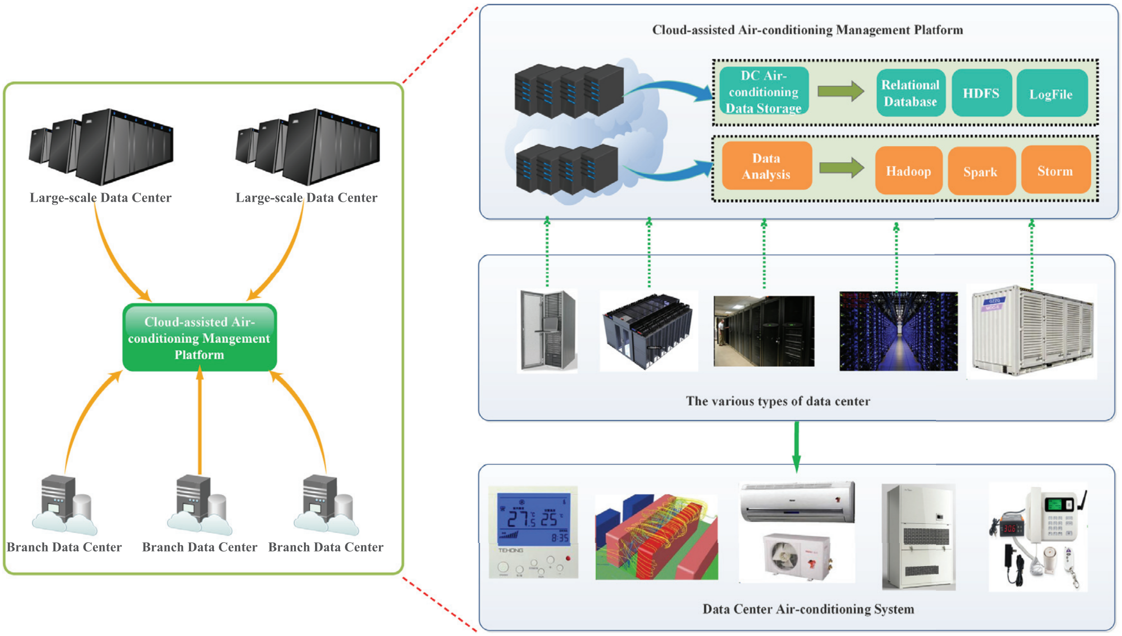

Fig. 2. Cloud-assisted green data center air conditioning system architecture.

The system architecture consists of the temperature control system and cloud management platform. The temperature control system provides cooling, ventilation, environment signal acquisition and transmission. The cloud management platform is responsible for data storage and query, environmental data monitoring, accessory device management, and Big Data-based system evaluation.

3.1. *Data center temperature control system*

The air conditioning system is the basis and guarantee for the stable operation of the DC. As shown in Fig. 3, the proposed air conditioning system mainly consists of five components: i) an environmental parameter monitor, ii) an air conditioning system, iii) a ventilation system, iv) a network communication system, and v) a multilevel intelligent temperature control system.

3.1.1. *Environmental parameter monitor*

A number of high-precision IT devices operate within a DC; therefore, unusually concentrated heat loads are easily generated. However, IT devices are often sensitive to changes in temperature and humidity. A sudden fluctuation in temperature may have an especially serious impact on the operating devices and even cause economic loss. Therefore, the stable status of temperature and humidity is the most important and basic requirement for a DC and must be supported by continuous environmental parameter monitoring.

Generally, the machine room area, rack layouts, and device quantity directly affect the temperature and humidity in the DC. Therefore, monitoring nodes should be flexibly deployed in the DC. To address this issue, we design a monitoring node integrated with a high-precision temperature and humidity sensor, which is small and easily deployed. The most important consideration is the convenience of installation in an existing DC.

Furthermore, a monitoring node is also deployed outside the DC for the following two reasons: i) The outside temperature affects the operation of the air conditioning system. For example, in colder regions, both temperature and humidity are extremely low, which may lead to problems and failure in the air conditioning system. ii) When the outside temperature and humidity are near the required parameters, some air conditioning can be closed, and the ventilation system should be opened to bring the natural cold air into the DC for energy-efficient cooling.

In particular, the power supply of the monitoring node is a combination of a battery and direct current supported by the DC power system. When the DC power system is available, the node is directly powered and charged by the DC. When the DC power system is unavailable, the node automatically switches to be powered by the battery. This power supply mechanism ensures high reliability of the environmental parameter monitor.

3.1.2. *Air conditioning system*

Considering compatibility and economy, we propose a lightweight reconstructed approach to integrate a ZigBee module into the existing air conditioning system. Specifically, the sensors are installed on the air conditioner to monitor the operating conditions and parameters, which can be used for device failure detection, analysis and forecasting through Big Data. Meanwhile, the sensors collect the information on power consumption, which provides guidance for energy optimization.

3.1.3. *Ventilation system*

To save energy, it is essential to introduce natural air into the DC for cooling. Therefore, we deploy ZigBee temperature

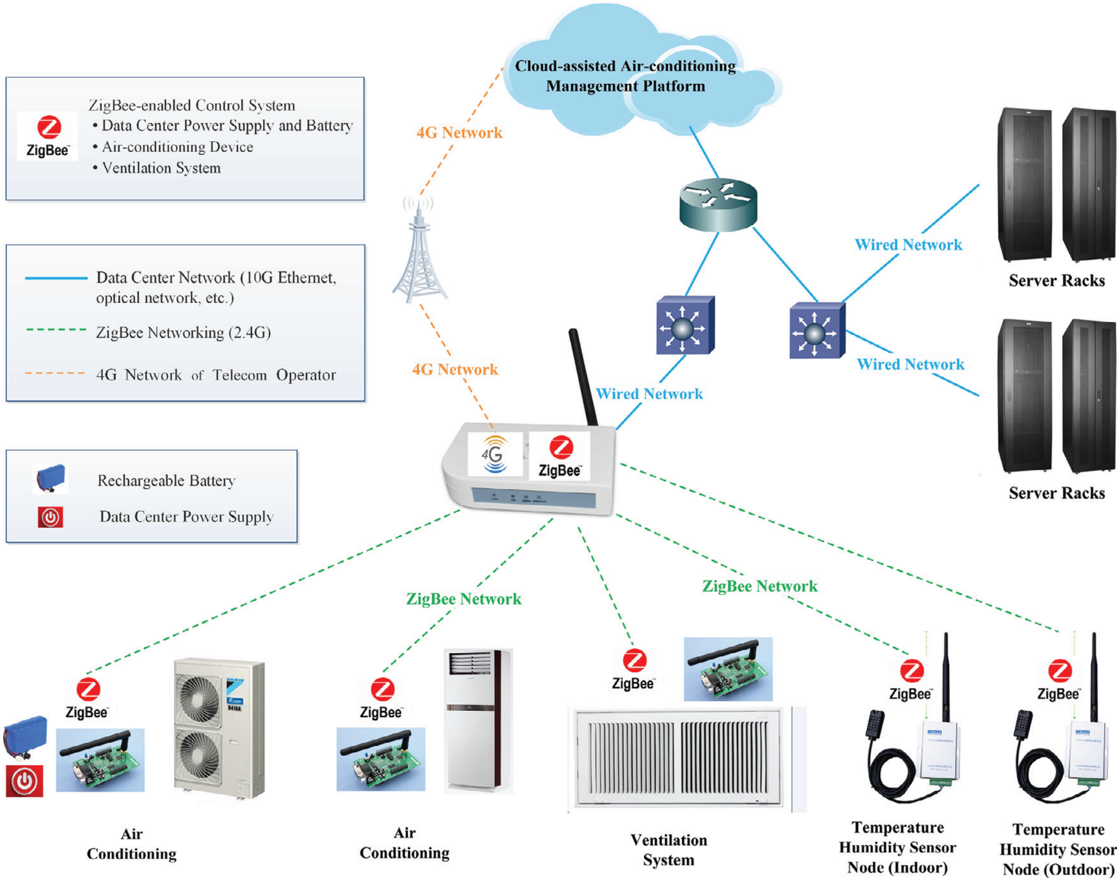

Fig. 3. Data center air conditioning system.

and humidity sensors at the vents to provide the basis for controlling the ventilation system. Furthermore, air filtering devices should be deployed to prevent air pollution in the DC.

3.1.4. Network communication system

The DC temperature control system provides two approaches for network communication: i) Because the DC usually provides a higher bandwidth and multiple Internet access points (AP), the ZigBee gateway can transmit sensory data and receive commands through a wired connection between the DC and the cloud. ii) In the case of emergencies such as DC network interruption, the ZigBee gateway is integrated with a 3G/4G module to provide reliable communications through the cellular network.

3.1.5. Multilevel intelligent temperature control system

The temperature control system contains three tiers: i) computer centre, ii) operation and maintenance centre, and iii) natural environment. IT equipment related to the data center is centrally deployed in the machine room, which is separated by transparent glass. Generally, most IT devices are placed in the computer centre with high requirements for a stable environment, whereas the operation and maintenance centre is near the computer centre; this is convenient for operational staff, who simply monitor general temperature and humidity. Hence, the computer centre and operation and maintenance centre are covered by separate air conditioning systems.

When encountering an abnormal temperature due to some emergency, the temperature control system will automatically open the door and vent between the computer centre and maintenance centre to use the air conditioning system in the maintenance centre to control the temperature in the computer centre. This multilevel intelligent temperature control system can not only deal with emergencies but also save energy consumption. When the temperature outside is detected to be relatively lower than that inside the computer centre, the system will automatically turn on the ventilation system, turn off some of the air conditioning, and bring the natural cold air into the computer centre for energy-efficient cooling.

3.2. Cloud-enabled management platform

The cloud-enabled management platform is the controlling centre of the DC air conditioning system. As shown in Fig. 4, its core functions include data storage and Big Data analysis. Moreover, various applications can be developed based on this platform to provide monitoring and management for the DC air conditioning system.

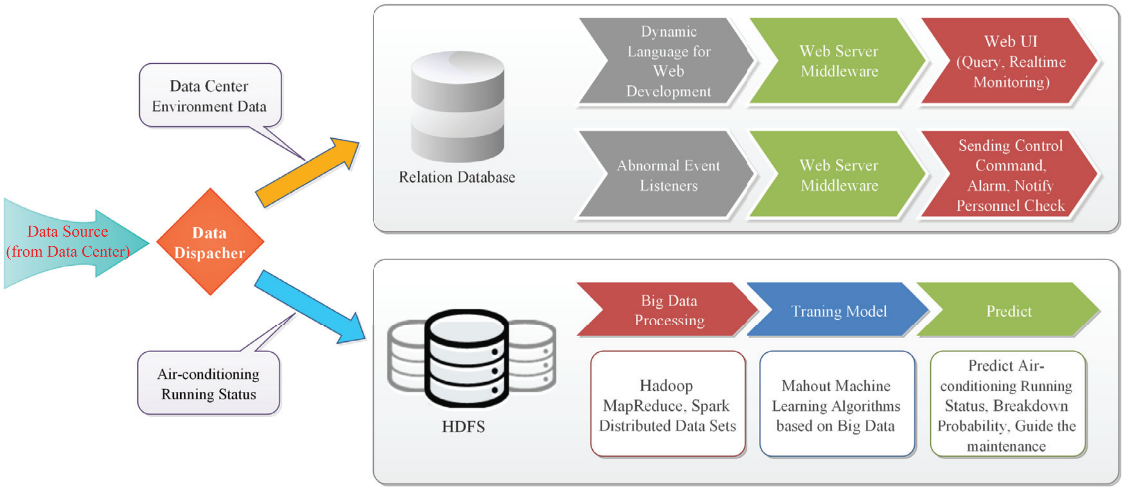

Fig. 4. Cloud-enabled management platform for air conditioning system.

3.2.1. Data storage

To achieve real-time monitoring of the environment and air conditioning devices in the DC, the sensors are expected to collect data at short intervals. As shown in Fig. 4, the sensory data are transmitted to the cloud and stored in a Relational Database Management System (RDBMS) and a Big Data storage system i.e., a Hadoop Distributed File System (HDFS) [26,27], after the classification assisted by the Data Dispatcher.

The RDBMS is used to store structured data for quick query and operations, and we can develop dedicated applications though the database access interface. However, considering that the volume of data transmitted to the cloud is very large and includes various monitored information from multiple DCs, the RDBMS is not sufficient to provide effective management. Therefore, the history data in the RDBMS is exported to the HDFS to improve performance. Furthermore, the data that do not require real-time processing can be directly stored in the HDFS.

3.2.2. Big data analysis and prediction

The emerging Big Data technologies support efficient analysis of mass devices running information, which can help us understand device dissipation and detect fault symptoms. Specifically, running information is collected by the sensors installed in the air conditioning system and transmitted to the cloud to facilitate performance monitoring. Furthermore, the air conditioning maintenance can be guided by fault analysis and prediction based on Big Data, which extensively improves the effectiveness of air conditioning systems.

3.2.3. Upper-layer applications

Based on the data storage and Big Data analysis, various upper-layer applications can be developed to demonstrate operation status in real time and monitor failures of the DC air conditioning system. Especially for distributed small DCs, such as the base station DC, having 7 × 24 hour technical personnel on duty is impossible, so we can develop a notification application to timely inform the technical personnel of system failure via text message or email.

4. Design and implementation

4.1. Multilevel intelligent temperature control algorithm

Fig. 5 illustrates the detailed procedure of the multi-level intelligent temperature control algorithm. The sensors are deployed to sense the temperature of the computer centre (T_{DC}), the operation and maintenance centre (T_{OR}) and the natural environment (T_N). Moreover, three thresholds i.e., $T_{[1]}$, $T_{[2]}$ and $T_{[3]}$ are predetermined values. The detailed procedure is described as follows:

- If the temperature difference between the computer centre and the natural environment is greater than $T_{[1]}$ (i.e. $T_{DC} - T_N > T_{[1]}$), the ventilation system between the data center and the natural environment (denoted by $W_{DC-Nature}$) will be turned on.
- Otherwise, if the temperature difference between the computer centre and the maintenance centre is greater than $T_{[2]}$, i.e. $T_{DC} - T_N > T_{[2]}$, the ventilation system between the data center and the operation and maintenance centre (W_{DC-OR}) will be turned on.
- Otherwise, if the temperature in the computer centre is greater than $T_{[3]}$, the air conditioner in the computer centre will be turned on.
- If none of the above conditions is fulfilled, the temperature in the computer centre is normal, and the system will switch to the energy-saving mode by turning off some of the air conditioning.

In response to emergencies, two thresholds T_{alert} and $T_{\max}$ must be defined, and the detailed warning procedure is described as follows:

- When $T_{alert} < T_{DC} < T_{\max}$, the air conditioning system in the computer centre is turned on, and a warning message is sent to DC managing personnel.
- When $T_{DC} > T_{\max}$, there is a very high-emergency situation. The ventilation system W_{DC-OR}, $W_{DC-Nature}$ and the air conditioning system in the computer centre (A_{DC}) and the operation and maintenance centre (A_{OR}) must be turned on immediately to lower the temperature as soon

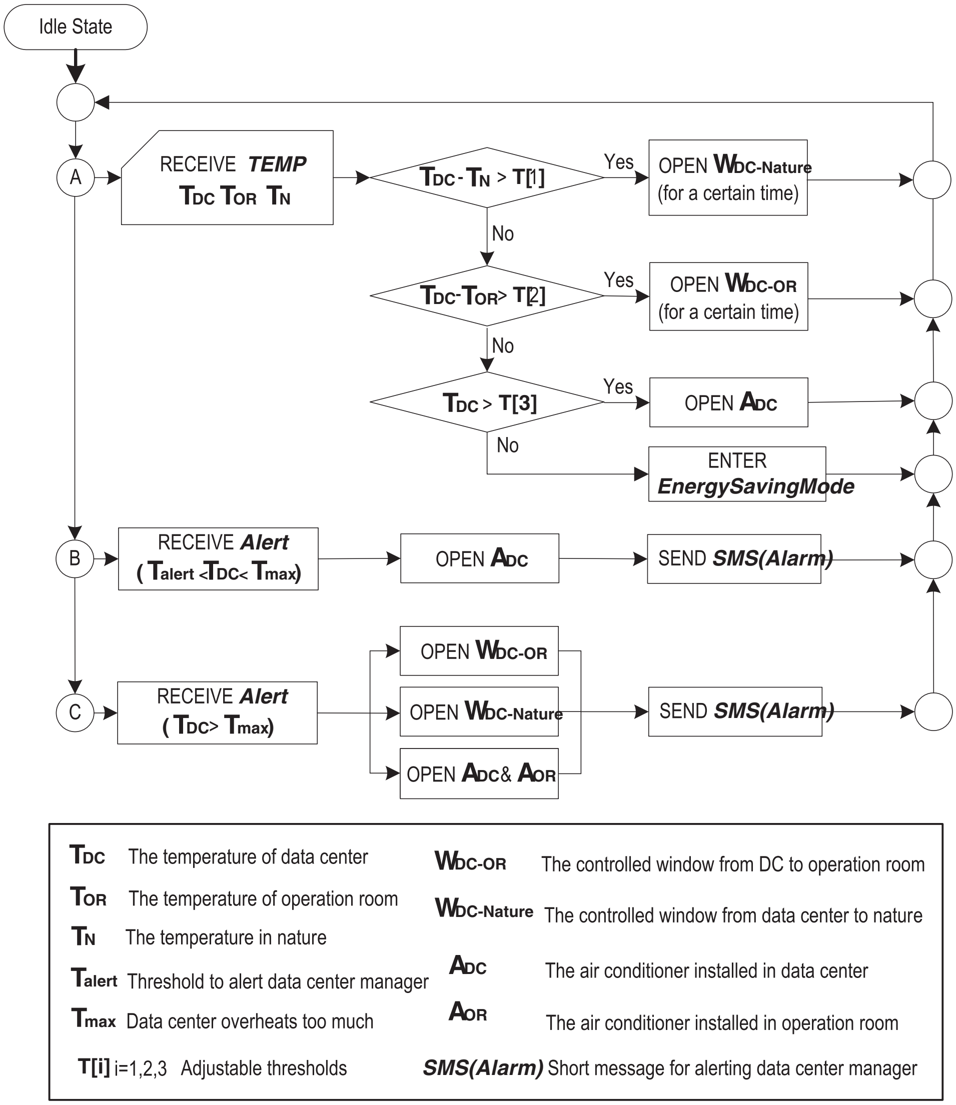

Fig. 5. Multilevel smart temperature adjustment strategy for green DCs.

as possible. Moreover, a warning message is sent to the DC managers.

4.2. Sensor networks in DCs

As shown in Fig. 3, the sensors deployed in the DC are organized in sensor networks, and the sensors transmit the sensed environmental data to the cloud platform via the sensor networks. Generally, communications between nodes inside the sensor network are based on short radio technology, such as ZigBee, which is adopted in the proposed system.

ZigBee is a low-speed and short-distance wireless communication protocol following the IEEE 802.15.4 standard, which supports up to 65,000 nodes. In the proposed system, the ZigBee networks includes the following three types of devices (nodes):

- **ZigBee Coordinator**: used to start and control the network and store network information.
- **ZigBee Router**: used to extend the network coverage, realize dynamic routing and prevent network jamming and device failure.
- **ZigBee Terminal**: used to collect the environmental data.

ZigBee supports Star Topology, Tree Topology and Mesh Topology. As shown in Fig. 6, we deploy a hybrid Star Tree Topology. When the DC area is small and there are few obstacles between the terminal and the coordinator, Star Topology is applicable. When the DC area is large and exceeds the maximum transmission distance between ZigBee nodes (generally 100 m) or there are several server racks between the terminal and the coordinator, deployment of Tree Topology supporting multi-hop transmission is suitable.

4.3. Environment monitoring node design

The environment monitoring node must be integrated with several sensors to collect complex environmental data.

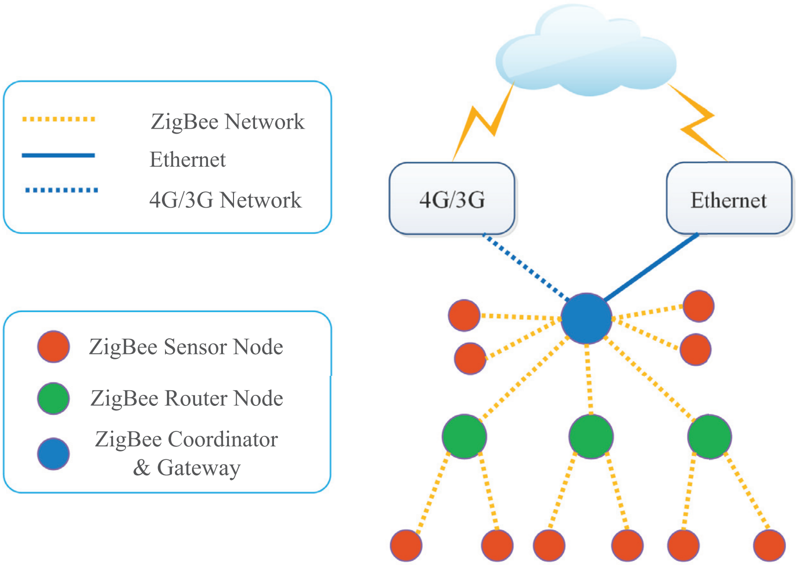

Fig. 6. Topological structure of the data center sensor network.

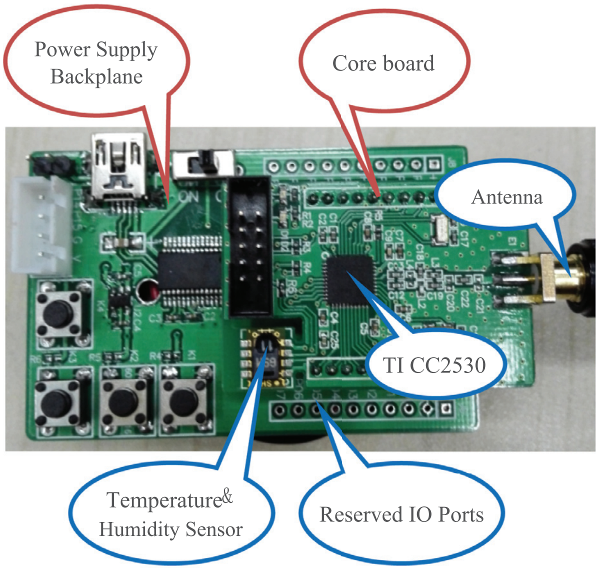

Fig. 7. Data center environment monitoring node.

In the proposed scheme, a CC2530 SoC chip produced by TI is used as the control chip of the sensor node, which is integrated with 256 KB of memory, 8 KB of RAM, and 1 high-performance RF transceiver and supports three types of power modes. There is a built-in temperature sensor on the CC2530, but its accuracy is insufficient. Therefore, the SHT1X temperature and humidity sensor is integrated on the sensor node, which has the advantages of high reliability and stability, fast response and strong anti-interference. Fig. 7 illustrates the design of the environment monitoring nodes.

4.4. Gateway design

The ZigBee gateway serves as a bridge between the ZigBee network and the Internet, which supports various network protocols in addition to ZigBee. As shown in Fig. 8, the gateway consists of the hardware layer, software layer and application layer. The hardware layer includes the gateway microprocessor, communication modules, conversion interfaces, etc. The software layer includes the embedded operating system, protocol stack and protocol conversion components. The application layer provides runtime for upper-layer applications.

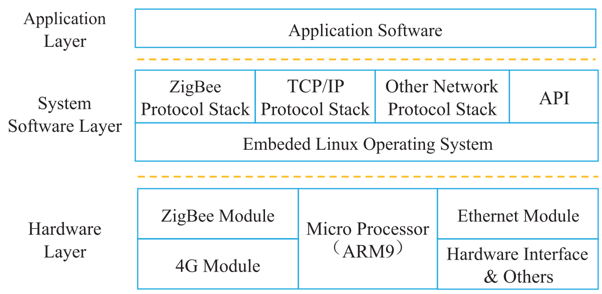

Fig. 8. ZigBee gateway framework.

5. Experiments and Evaluation

5.1. Testing and evaluation environment

The feasibility of the proposed system is validated in a small DC. The basic information of the DC is described in Table 1, and Fig. 9 illustrates the actual deployment of the multilevel smart air conditioning system.

5.2. Experiments

To demonstrate the topology of the sensor network in this DC and visualize the sensory data, we developed mobile applications on the Android platform.

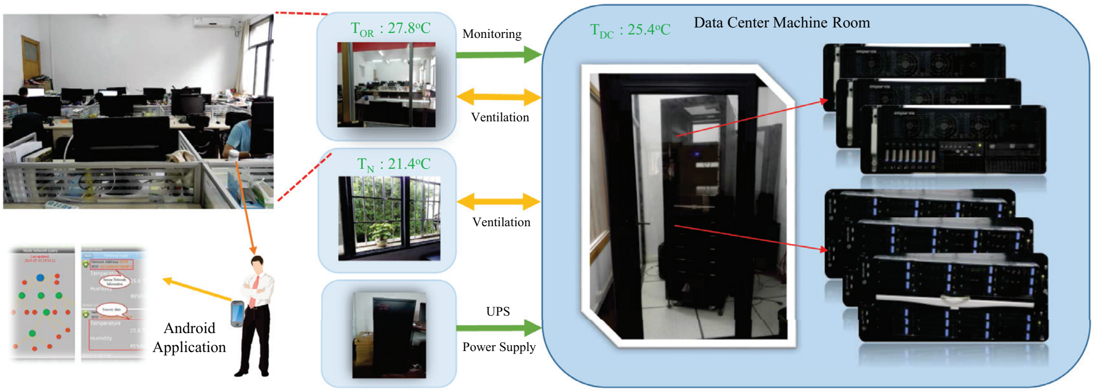

Fig. 9. Actual deployment effect of the multilevel intelligent air conditioning system.

Table 1
Basic information of the data center.

Parameter Type	Value	Remark
Area	20 m^2	The area of the data center room
Number of Air Conditioners	3	Modified household air conditioning for supporting ZigBee
Number of Racks	6	2.2m × 0.6m × 0.90m (*Height* × *Width* × *Depth*)
Number of Sensor Nodes	10	Scattered in different locations in the room

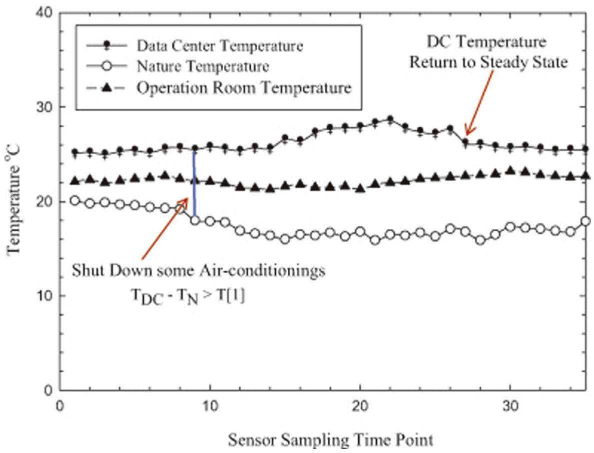

Fig. 10. Data center temperature regulation.

As shown in Fig. 10, when the natural environment temperature is obviously lower than that in the computer centre, the system will automatically turn off some of the air conditioning and turn on the ventilation system between the computer centre and the natural environment to introduce cold air into the DC for energy-efficient cooling. The temperature then rises slightly, but is still in the range of the permissible temperature, because the cold air is not brought into the DC in time. Starting from the 27th sampling time point, the temperature tends to a steady state. Thus, assisted by natural cold air, the temperature can be controlled with lower energy consumption.

Moreover, Fig. 10 illustrates that the temperature difference between the operation and maintenance centre and the computer centre does not exceed the threshold, so the ventilation system between them is not turned on.

For further validation, the electricity consumption in one month is statistically analysed. This DC is located in a large day-and-night temperature difference area, so the ventilation system between the computer centre and the natural environment is automatically turned on at night, whereas some of the air conditioning is turned off. In the daytime, if the temperature difference between the computer centre and the natural environment is less than the threshold, the ventilation system will be turned off, and the air conditioning will be turned on. As shown in Fig. 11, with the assistance of the multilevel smart temperature control system, the percentage of the air conditioning system accounting

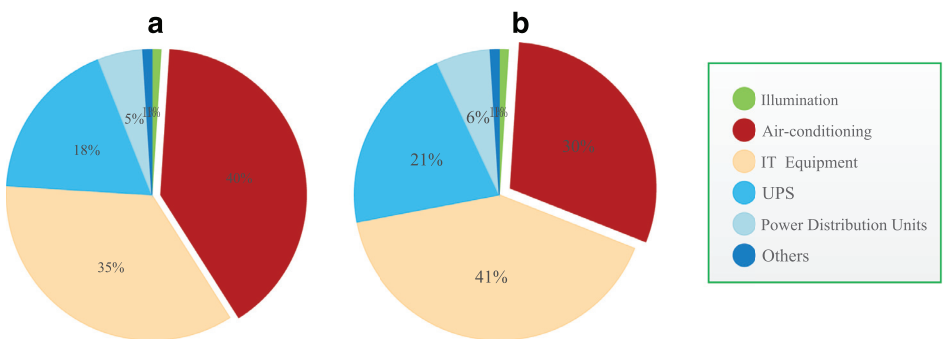

Fig. 11. Percentage of the air conditioning system accounting for the total power consumption in the data center.

for the total power consumption in the DC is reduced by 10%.

6. Conclusion

In this paper, a green DC temperature control system assisted by cloud computing is proposed. This paper presents the detailed functions of each system component. Moreover, based on an actual deployment in a small DC, the experimental result validates that the proposed scheme can effectively reduce the energy consumption without degrading the cooling effect.

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