# Multi-layer Method for Data Center Cooling Control and System Integration

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Abstract: This paper describes an integral management hierarchical structure for data center server room ventilation and IT equipment cooling based on multi-layer approach. The approach contains two hierarchical layers, the lower layer is responsible to assure the right cooling power of each server-rack avoiding overcooling and waste of energy. The upper layer is responsible to perform the tasks of optimization, supervision and coordination of all subsystems in the lower layer for holistic control. The approach aim is to make data centers more energy efficient, here we focus on proposing a general approach to improve the efficiency of their thermal cooling systems.

## 1 INTRODUCTION

Due to rapid growth of large data centers worldwide, data centers become energy intensive processes accounting for over 1% of the worlds electricity usage (Koomey, 2011). Energy efficiency becomes even more important for these data centers. IT equipment and cooling infrastructure are the two major power consumers. Investigation showed that energy consumption by cooling data center IT equipment is between 30% and 55% of data center total operation energy consumption (Song et al., 2015). Several data center cooling and cooling control have been investigated. Data center Power Usage Effectiveness (PUE) were well defined (Patterson, 2012). PUE is one of most used data center matrices. The distribution of airflow and resulting cooling in a data center was studied with using computational fluid dynamics (CFD) to find out various factors affecting the airflow (Patankar, 2010). Cooling control for data center operation with higher ambient temperature was studied by Ahuja et al. (Ahuja et al., 2011). A platform-assisted thermal management approach was applied to use new sensors providing server airflow and server outlet temperature to improve control of the data centers cooling solution. An online control algorithm of data center power supply under uncertain demand and renewable energy was developed by applying two-stage Lyapunov optimization techniques to make online decisions on fully utilizing renewable energy and two-timescale power purchasing and uninterruptible power source (UPS) charging/discharging in a complementary manner to minimize operation cost (Deng et al., 2013). A comprehensive model of the data center cooling power consumption was developed by Zhang, et al. (Zhang et al., 2016). In this model, power consumptions of servers, racks, CRAH, chiller, cooling tower, UPS and PDU were modeled to cover data center design and operation scenarios. The models was intended to be used for the data center cooling simulation and control. Optimal fan speed control for data center servers was investigated by Wang, et al. (Wang et al., 2009). A multi-input multi-output fan controller that utilizes thermal models was developed from first-principles to manipulate the operation of fans. The controller tunes the speeds of individual fans proactively based on prediction of the sever temperatures. Controlling the temperature rise during the power failure is crucial issue for data center availability. In order to analyze the temperature rise characteristics, a real-time transient thermal model to demonstrate the heating of a data center following the loss of utility power was developed by Lin et al. (Lin et al., 2014). Strategies of placing critical cooling equipment on backup power, maintaining adequate reserve cooling capacity, and employing thermal storage, are provided and checked whether they can handle the power outages in a predictable means using this model. Control strategies were recommended to achieve the desired temperature control during the power outages. A three-level data center control architecture with server level, zone level and data cen-



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ter level was proposed by Parolini (Parolini, 2012). At the data center level, a single controller directs the lower level controllers and the set points for the computer room air conditioning (CRAC) or computer room air handler (CRAH) units are defined, it defines the values of the reference temperature vector at every time. At the zone level, multiple controllers operate and manage those controllers and systems related to zones. A framework integrating online learning and optimal decision is proposed to make real-time control of the airflow and temperature distribution (Xiong and Zhang, 2016). By online learning, the model is updated in run time according to newly arrived samples. At the same time, control actions are decided based on the current process model to figure out the best values of control variables to optimize the control performance. Data center thermal management with flexible humidity control was studied by Berezovskaya et al. (Berezovskaya et al., 2016). Combined cooling and humidity control strategy showed significant energy consumption reduction. Cyber-physical design of data center cooling systems was investigated by Mousavi et al. (Mousavi et al., 2015). Distributed adaptive automation architecture was designed to improve energy efficiency, flexibility, better decision-making ability and controlling the cooling systems In the conventional data center with hot aisle/cold aisle, cold air generated by the cooling system is supplied through a plenum under the floor and perforated air flow panels. The cold air flows up horizontally entering server rack from front side and leaving from back side. The classical way to control it is to consider all server racks as an entire cooling load and the cooling system control this load as a whole. This paper proposes an integrated approach, where individual control for each server is performance in coordination with a global control of the overall cooling equipment of the data center. The paper has the following structure: This section has presented the introduction and relevant previous works. Section 2 describes the multi-layer structure for decisions and control. Section 3 presents functions of the proposed multi-layer methodology for data center cooling control. Finally, conclusions are summarized in section 4.

## 2 MULTI-LAYER STRUCTURE FOR DECISIONS AND CONTROL

In order to obtain the holistic control of a data center power, IT and cooling system, it is proposed a hierarchical structure for decisions and control, where the information about the process has a different accuracy and complexity, and the amount of exchanged information and its update frequency changes according to the layer. At the upper layer the control strategy manages a big amount of complex information. In the upper layer each subsystems have different frequency updates, for example, optimization and CFD subsystems may require hours, a failure detected in an equipment can be monthly or bimonthly, but others subsystems are able to exchange information faster. On the other hand, at the lowest level the control strategy is based on the principle of increasing accuracy and decreasing intelligence and complexity, but its frequency increases to the range required for the equipment, for example, seconds for cooling units, milliseconds for power devices. The way to achieve the control implementation is to perform the control of each server-rack using local control devices in the lower control layer and data center coordination in the upper control layer. This model establishes the different functional layers used for controlling a data center. Figure 1 shows the control scheme.

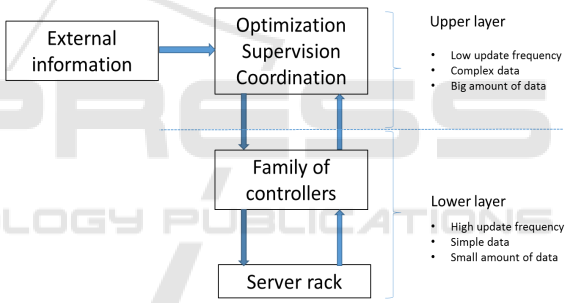


Figure 1: Multi-layer method for server-rack cooling control.

The method proposes system integration, since this ensures the control of the processes in their natural form. Then, coordination in the upper layer is achieved through the reception of information about the states of the processes (ascending path to the upper layer) and the transmission of commands to the processes (descending path to the lower layer). The exchange of information is performed between different actors in the upper layer and local controllers in the lower layer. The existence of communication devices and computer networks that ensures communication among the control equipment is a fundamental factor to achieve integration. The lower layer is responsible for the local continuous control of each server rack. Each one is controlled by local control schemes, and they represent the direct controllers over the controlled variables. In upper layer the tasks of optimization, supervision and coordination for server racks to achieve a coherent operation among data center are accomplished. The operation of server rack and its direct controller is described as the operation regions, in which the parameters and rates stay constant for an undefined time until there appears a change of the operation state. The upper layer determines the operation region for the lower layer and generates the parameters for the direct control level. Signals coming into this layer allow determination of the state of the process units as well as the production objectives that have been fixed in the superior layer. At this level, local supervisors for each subsystem are defined. They determine the operation mode of each unit, and the changes of the parameters or local rules in the lower layer. With a superior hierarchy, a global coordinator is responsible to fix the directives for each one of the local cooling controllers, as a function of the joint operation mode of the entire data center.

## 2.1 Layer Functionalities

This approach provides a method for data center cooling control. The method includes at least two cooling control layers, a lower layer and an upper layer. In the lower layer, see figure 2, electrical power demand of each server or IT load is used as feedforward signal for estimating the cooling power required for each rack. Basic temperature sensor network and air flow sensors are required to measure each server rack. Humidity sensors do not need to be installed at each server rack, but with one or two in each server row. Information about temperatures and air flow of each server rack are used as feedback signal to achieve the right dose of power cooling on the server. In the low layer a network of humidity, temperature and airflow sensors are used for controlling the humidity, temperature and air flow distribution on the room. Temperature of server rack, outlet temperature or inlet temperature and air flow can be used as feedback signal.

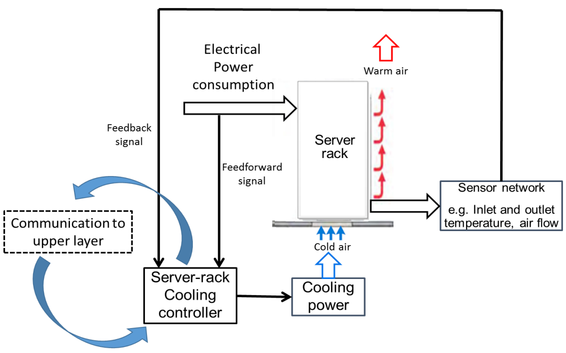


Figure 2: Lower layer.

The upper cooling control layer is responsible for supervising and coordinating local controller in the lower layer and optimizing the total cooling power and the distribution of cooling power required for each server rack. Figure 3 shows the diagram of a coordinator, in this case, it gets information about cooling power of each server rack, sensor network and cooling equipment status. Using this information the coordinator manage all data and send to the lower layer parameters and configurations for each single cooling equipment and server-rack controllers. A similar scheme can be used to coordinate the power devices e.g. uninterruptible power source (UPS), power distribution unit (PDU) and batteries. Coordinators manage the communication to the lower layer at the frequency required for the lower layer units, but also, can get updated information for other subsystems of the upper layer at low frequency of the range of hours e.g CFD subsystem or optimization subsystem.

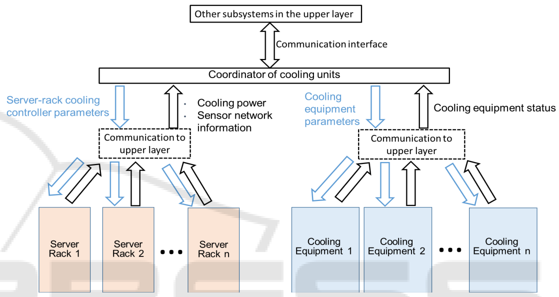


Figure 3: Coordinator on the upper layer.

In this upper layer tools are used, which manage a big amount of complex data with low update frequency for achieving the optimal distribution of cooling power, which means air flow, temperature and humidity distribution and patterns and generate parameters for the lower layer cooling control. The upper layer can be used or combined many different tools, including, but not limited to CFD simulations, machine learning, artificial intelligence and so on which are all less time critical compared to the operations in the lower layer. These tools optimize the global demand of cooling power of the data center taking into account complex data e.g. actual operating conditions and future expectations of IT load, electricity price, power availability, and data center operating conditions related to electrical and cooling power consumption. The upper layer provides to the lower layer, operational information for the cooling units, for example, CRAC/CRAH fan speed, air temperature and humidity references for the equipment. A general diagram of the upper layer is illustrated in figure 4. It shows how subsystems exchange information in the upper layer through a common communication infrastructure. For example, if the analytic subsystem predicts an imminent failure on a cooling equipment, this information can be sent to the coordinator of cooling units. This coordinator turns off the corresponding cooling equipment and sends a new set of parameters for the other server-rack cooling controllers and cooling equipment. Coordinators exchange information with the lower layer at the frequency required for the lower layer, but it is based on information obtained from other subsystem which can exchange information at low frequency, hours in the case of CFD simulations and electricity price changes or monthly when a failure is detected.

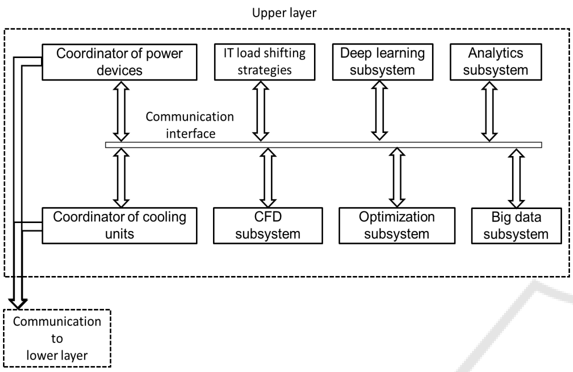


Figure 4: General diagram of the upper layer.

The upper layer provides also recommendations for operational information for IT load, for example, the servers that must be turn off according to the probability of being used in the near future, placing and moving IT loads into proper locations can make the cooling infrastructure operate more efficiently and hence can result in substantial reduction in cooling power. This methodology aims a holistic management of the data center for avoiding waste of energy due to for example overcooling.

## 3 FUNCTION DEFINITION AND METHOD DISCUSSION

A number of functions have been defined in the upper layer of the developed method include the following,

- CFD generated data for cooling control. Parameterized CFD simulation tool is required to be able to simulate a data center air flow as well as temperature, humidity distributions and patterns in order to generate parameters for cooling control. This CFD tool is also able to simulate air flow pattern and temperature distribution in air plenum and identify correlations among each cooling unit and individual server rack with a degree of influence, see Figure 5. Since CFD will take a long time to generate results, the CFD simulations should be pre-run in order to be used for real time control.
- Use of operation historical data. Based on prestored operation historical data and the above described CFD simulated data, offline machine learning, deep learning, fuzzy logic, and neural network modeling will provide sufficient data and information for advanced control and can even be used for failure detection. (Machine learning itself is limited by operation parameter ranges, for example, rack supply air temperature is normally between 18 to 27C, however, CFD simulated data are not limited in such a range, therefore, combined CFD and machine learning will provide complete information for cooing control).
- Ventilation and air flow control method. To reach data center rack-level cooling control, cooling air needs to be adjusted or controlled to individual server rack. In this approach the distributed air flow control method is extended to include under floor (air plenum) adjustable air separation and adjustable ventilation shutters in server racks. The design of the adjustable air separation is based on CFD simulation for a specific data center layout. Even in cases where many cables are laid in the air plenum, the air separation can be installed. For each blade server, one adjustable shutter will be installed.
- Power consumption data of power devices. Each power devices, e.g., UPS, PDU, and battery are monitored with online power consumption.
- IT load and load shifting strategies for cooling control. The upper layer can simulate load shifting strategies while all customer service level agreements are fulfilled. Furthermore, the system can simulate the arrival of new IT loads corresponding to IT load predictions which are learnt from historical data. Both, the arrival of new IT jobs and the analysis of possible IT load migrations can support the cooling control of the whole data center.
- Climate data and electrical price. These data will be used for upper layer to decide which cooling strategies to apply, free air cooling or mechanic cooling. The upper layer will take care of energy source optimization based on electrical price and other available energy sources.

Provided main cooling parameters will be as following,

- Supply cooling air temperature in rack-level,
- Air flow flowrate in rack-level,
- Humidity in row or rack level,

- Flow control through adjust the air separation angle, close/open or through ventilation ducks,
- CRAC/CRAH fan speed, air temperature,
- Cooling water flow and temperature in mechanical cooling system.

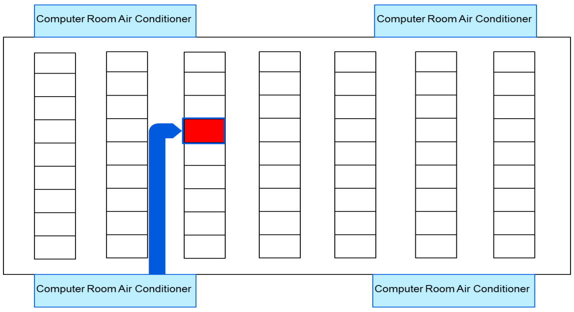


Figure 5: CFD simulation of cooling air flow patterns from CRAC/CRAH.

Modern data centers are equipped with Data Center Infrastructure Management (DCIM), for example, ABB Decathlon for data center. DCIM is a software platform to manage data center IT facilities, cooling system and power supply system with a number of functions including process monitoring and control. The methodology developed in this work can be implemented to DCIM to solve the problem of hot spots and over cooling, which are common problems in data centers. This approach can be used for data center zone-level, rack-level and server-level cooling control. The principal advantage of the proposed approach is the capacity of holistic control, where decisions are taken based on integrated information of different subsystems, for example power devices, IT load, deep learning subsystems, Computational fluid dynamics simulations, optimization routines, big data algorithms. All this abstract information in the upper layer is translated to the server-rack cooling controller in the lower layer, through a coordinator of the cooling units, which is responsible for providing the parameters for the server-rack cooling controller. Thus, the right dosage of cooling power suits the particular needs of each server-rack. This is another benefit of this methodology as opposed to the classical control way, which is to consider all server racks as an entire cooling load and the control scheme manages the entire load as a whole.

## 4 CONCLUSIONS

This paper proposed a cross layer methodology for facing the global cooling control of data center. The multi-layer approach includes two layers. A lower layer which is responsible of the cooling control at rack and the server level. It uses the electrical power consumption of the servers and information provided by the sensor network e.g. inlet and outlet temperature, air flow. And an upper layer which incorporates Computational fluid dynamics simulations, machine learning, and artificial intelligence (all upfront to the real operation of the data center) to provide control parameters and configurations to the lower layer. The upper layer integrated management of all the variables that have influence on the cooling performance of the data center air flow, temperature, and humidity and provides recommendations for turning off servers, placing, and moving the IT load according to thermal distribution of the data center and customer service level agreements. In the future, we will implement developed method and structure to ABB Decathlon software platform to extend Decathlon functionalities and capacity.

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