Experiences and Learned Lessons from an Air Free-Cooled Tropical Data Center Testbed

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ABSTRACT

The air free-cooling has been long thought infeasible in tropics due to the unique challenges of year-round high ambient temperature and relative humidity. In recent years, the increasing availability of servers that can tolerate higher temperatures and relative humidity levels sheds light upon the feasibility of the air free-cooling to enhance the data center energy efficiency. However, building an air free-cooled data center in the tropics requires extensive experiments to understand the details of how the tropical environment conditions will affect data center power consumption, computing throughput, and server hardware reliability. Thus, together with multiple partners in data center industry and research, we conducted a project that designs, builds, and experiments with an air free-cooled data center testbed consisting of three server rooms hosting 12 server racks with 60 kW total power rating. This paper presents the key observations, experiences and learned lessons obtained from our project. The experiments show that (1) the air free-cooling design that uses fans only can reduce the power usage effectiveness (PUE) by 38%, compared to the global average PUE, (2) the tropics' year-round high temperatures up to 37°C do not impede the air free-cooling, and (3) the implementation of the air free-cooled data centers in tropics requires special cares to deal with airborne contaminants to avoid fast corrosion rate and dust-induced server faults.

CCS CONCEPTS

• **Applied computing** → **Data centers**; • **General and reference** → *Experimentation.*

KEYWORDS

Data center, free cooling, performance, reliability

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1 INTRODUCTION

Air free-cooling that utilizes outside cold air to cool the information technology (IT) equipment has been increasingly used to improve the energy efficiency of data centers (DCs) [3]. However, air free-cooling in the tropics has been long thought infeasible from the intuition that the high temperature and relative humidity (RH) of the air supplied to the servers will undermine their performance and reliability. On the other hand, the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) has been working for years on expanding the suggested allowable temperature and RH ranges for IT equipment. For instance, the servers compliant with ASHRAE's Class A3 can operate continuously and reliably when the temperature and RH of the supply air are up to 40°C and 90%, respectively. This sheds light on the possibility of air free-cooled DCs in tropical climate since the maximum record temperature in our tropical region, i.e., Singapore, is 37°C only and the ambient RH is in general lower than 90%.

However, the ASHRAE's relaxed temperature and RH requirements are for traditional DCs that recirculate the clean air within the enclosed DC building only. The air free-cooled DCs that continuously bring the outside air into the server rooms will introduce extra challenges due to various affecting factors such as the ambient temperature and RH, air volume flow rate, and cleanness level of the supply air. Therefore, it is essential to investigate the details of how the affecting factors of tropical environment conditions will affect DC power consumption, and the computing performance and reliability of the IT equipment. To achieve the goal, together with multiple partners in DC industry and research, we designed, constructed, and experimented with an air free-cooled

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DC testbed consisting of three server rooms located in two DC operators' premises that are in Singapore. The testbed hosts 12 server racks with 60 kW total power rating. We have conducted 18-month experiments on the built testbed, in which the cooling conditions (e.g., cold aisle temperature and air flow rate setpoints) and the server operating parameters (e.g., CPU utilization, hard disk drive (HDD) read/write speed, and memory copying parameters) are controlled in specified ranges. During the experiments, various types of sensor data, including environmental, energy, performance, and reliability measurements are collected to analyze the impact of different environmental conditions on DC energy efficiency, hardware reliability, and computing performance.

Several DC providers such as Facebook and Google have used the air free-cooling to improve the energy efficiency of their DCs. However, they often use the air free-cooling only for cold and dry locations where the climate allows the outside air to be used to cool the server in the major time of the year. For instance, Facebook has built free-cooled DCs in Prineville, Oregon and reported an annualized power usage effectiveness (PUE) of 1.07 [9]. However, Facebook does not release any technical details. To the best of our knowledge, this is the first work that experiments with a real air free-cooled DC tesbted with failures of hardware components allowed under controllable and challenging environmental conditions. A number of works [2, 7, 10] have studied the impact of DC operating environment condition on the performance and reliability of servers. Sensor networks have been deployed in DCs to achieve real-time monitoring of servers' ambient conditions [5, 6]. For example, the Microsoft researchers [6] implemented a DC Genome system using wireless sensors called *Genomotes* to monitor the environmental conditions in their production data centers. However, those works mostly relied on the data collected from production DCs. Therefore, their observations may not cover the impact of all possible temperature conditions under the free cooling in the tropics. In addition, several studies [2, 8] have set up DC testbeds using thermal chambers to evaluate the impact of the high temperatures on servers' performance. However, the tightly controlled environments in the small-scale thermal chambers fall short of capturing a full spectrum of affecting factors in the real air free-cooling setup.

Different from those existing works that study impacts of the temperature on the server's performance and reliability, our work builds a real air free-cooled DC testbed and conducts experiments spanned 18 months to capture many realistic affecting factors, including the temperature, RH, air volume flow rate, and supply air's corrosive gases and dusts. Our experimental results measured by physical sensors monitoring environmental conditions and power usage, as well as servers' built-in sensors provide the details of how the realistic tropical environment conditions affect DC power consumption, computing throughput, and server hardware reliability.

In this paper, from our experiments on the testbed, we draw the key observations, experiences and learned lessons as follows.

- The air free-cooling design that uses fans only to control the volume flow rate of the outside air supplied to the servers can reduce the PUE by 38%, compared with the global average PUE of 1.7 [4].
- The servers can operate without computing performance degradation under combined impact of various realistic factors, including temperature up to 37°C and RH above 90%. In other words, the tropics' year-round high temperatures up to 37°C do not impede the air free-cooling in the tropics.
- The implementation of the air free-cooled DCs in tropics requires special cares to deal with airborne contaminants to avoid fast corrosion rate and dust-induced server faults.
- The existing DCs operated in enclosed buildings can increase their temperature setpoints for better energy efficiency without degrading server computing performance.

The remainder of this paper is organized as follows. Section 2 describes the design and construction of the testbed. Section 3 presents the experiments on the testbed and the key results of server performance and energy usage. Section 4 details the IT equipment failures occurred during the course of the experiments. Section 5 presents the learned lessons and discusses several issues. Section 6 concludes this paper.

2 DESIGN AND CONSTRUCTION OF TESTBED

This section describes the design of the testbed and our experiences in constructing and configuring the testbed.

2.1 Design of Testbed

We design the testbed with three objectives. First, on the testbed, we can maintain the condition of the air supplied to the IT equipment at a certain setpoint for a period of time (e.g., several days). The condition includes three aspects that are often considered important for IT equipment performance and reliability, i.e., temperature, RH, and air volume flow rate. The setpoint can be adjusted within a wide range, such that we can evaluate the performance of the IT equipment under various conditions. In other words, we can run the testbed in a *controlled* mode. However, we later found that RH control in a wide range is difficult, which will be discussed shortly. Second, we can run the testbed in an *uncontrolled* mode, in that we just use the outside air without adjusting its condition to take away the heat generated by the IT equipment. We aim to run the testbed in this uncontrolled mode for an extended period of time to understand the direct impact of the outside air on the IT equipment and the achievable energy saving. Third, the testbed should include a standard server room with well controlled conditions to generate the baseline results.

To meet the above three objectives, we design a testbed consisting of three server rooms that are referred to as Room-A, Room-B, and Room-C in this paper. Room-A and Room-B are two side-by-side purposely built server rooms to support the aforementioned controlled and uncontrolled experiments. The side-by-side arrangement makes sure that they will inhale outside air with the same condition, enabling comparative experiments. We built these two server rooms in the premise of a commercial colocation DC operator that is referred to as Operator-A in this paper. As such, we may leverage the domain expertise of Operator-A in facility management, 24/7 monitoring, security assurance, emergency response, and etc. Room-C is a standard server room operated by another commercial colocation DC operator that is referred to as Operator-B in this paper.

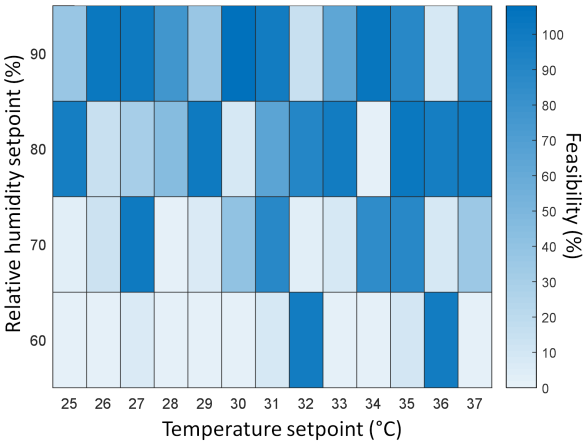


Figure 1: Feasibility of temperature/RH setpoints during Jul and Aug 2018 in the testbed area.

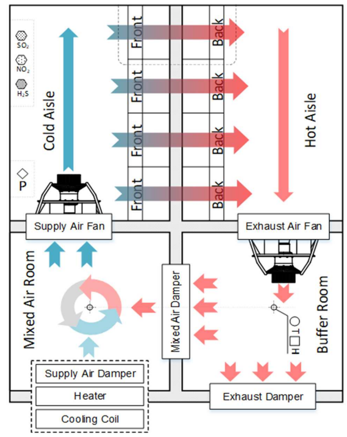


Figure 2: Design of Room-A/B. Room-B does not have heater.

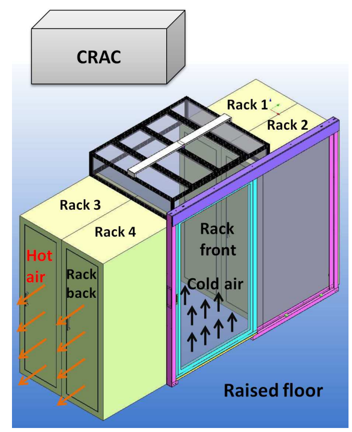


Figure 3: Design of Room-C and cold air containment.

The original testbed design objectives include RH control capability. However, from the discussions with facility suppliers and our study, we found that for Room-A and Room-B, implementing RH setpoints in a wide range in our tropical condition is costly and technically challenging. First, as Room-A and Room-B will continuously inhale outside air, from our industrial partner with extensive DC facility expertise, the commercially available dehumidifier and humidifier cannot sustain the RH and air volume flow rate setpoints specified in the experiment plan (cf. Section 3.1). Note that typical DCs often have enclosed environment, in that the air is circulated within the data center building. As they inhale a limited amount of air from the outside, they have low dehumidification demands. Second, we have also studied a possible energy-efficient *cooling-then-mixing* dehumidification approach. Specifically, it uses a cooling coil to condense and remove the water vapor contained in the air entering the server room and then mixes the dried cold air with a controlled portion of the hot air generated by the IT equipment to maintain the temperature of the air supplied to the IT equipment at the setpoint. However, for a total IT load of 20 kW in a server room, our simulation studies show that the ability of this dehumidification approach in maintaining the temperature and RH setpoints highly depends on the temperature and RH of the outside air. The grayscale in Fig. 1 shows the percentage of time in July and August 2018 in our testbed area, during which the corresponding temperature and RH setpoints on the x- and y-axis, respectively, can be maintained by the cooling-then-mixing approach. We can see that it is difficult to maintain low temperature and RH setpoints simultaneously for long periods of time.

Given the challenges in controlling RH in a wide range, we focus on maintaining the temperature and air volume flow rate setpoints in the design of Room-A and Room-B. Our design is as follows. Each of Room-A and Room-B is equipped with a cooling coil and multiple fans to move the air through the room. Fig. 2 shows the design of a single room. Room-A has a cooling coil and a heater to maintain the temperature of the air supplied to four IT racks. It has two fans, i.e., supply air fan and exhaust air fan, to move the air. In addition, it has three air dampers, i.e., supply air damper, exhaust damper, and mixed air damper. By setting the openness of the three dampers, we can control the percentage of the hot air generated by the IT equipment that will be mixed with the cold, relatively humid outside air to form warm, relatively dry air for the IT equipment. This design gives a certain level of RH control capability that can be used to reduce the negative impact of airborne contaminants on the reliability of the IT equipment. This issue will be discussed in Section 4 and Section 5. The details of this mixing control are presented in our previous study [12].

The only difference between Room-B and Room-A is that, Room-B does not have a heater. This reduces the equipment cost and does not impede our experiments, because we can assign the controlled experiments with high temperature setpoints to Room-A. After the designs of Room-A/B were generated, we contracted a third-party company to build a computational fluid dynamics (CFD) model based on our designs and perform extensive simulations to check whether the thermal properties of the two server rooms meet our requirements. Note that after the testbed was commissioned, the CFD model was improved by this company based on the data traces generated by the testbed to achieve a root mean square error (RMSE) of about 1.2°C in predicting temperatures in the server rooms.

Room-C is a standard private vault in a commercial colocation DC. It follows the typical raised floor design and has a computer room air conditioning (CRAC) unit. We purposely improved its energy efficiency to make it an optimistic baseline by adding a cold air containment design as illustrated in Fig. 3. The figure also illustrates the layout of the four IT racks and the air flows.

2.2 Construction of Testbed

The construction of Room-A/B undertaken by a contractor took about four months. Fig. 4(a) shows the two side-by-side storage rooms located within the premise of Operator-A that were later retrofitted into Room-A and Room-B. Figs. 4(b) and (c) show the exterior of Room-A and Room-B during and after the construction, respectively. As seen in Fig. 4(c), two supply air ducts were constructed such that there is sufficient space separation between the air inhaled and exhausted by Room-A/B. Air filters of Class

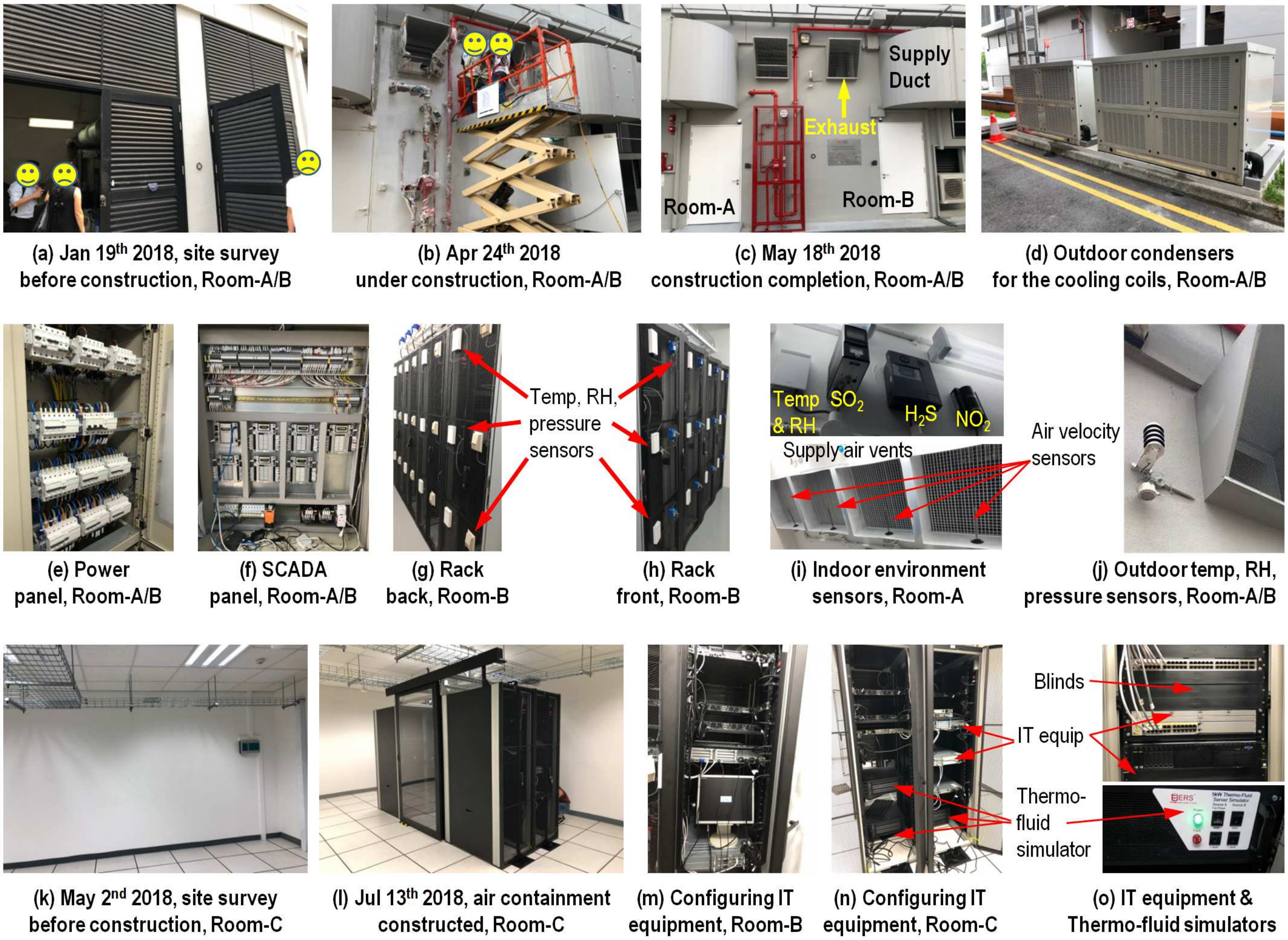


Figure 4: Construction and configuration of Room-A, Room-B, and Room-C of the testbed.

MERV-6 were installed in the air ducts to prevent PM10 and larger particles from entering the server rooms. The red pipelines shown in Fig. 4(c) belong to a fire protection system. Note that, as Room-A and Room-B would experience high temperatures at their hot aisles, the testbed must have a fire protection system with 24/7 monitoring. Fig. 4(d) shows the outdoor condensers for the cooling coils installed in Room-A/B. The distance from these condensers to Room-A/B is about 30 meters to reduce the heat recirculation from the condensers to the two rooms. Figs. 4(e) and (f) show the power and Supervisory Control and Data Acquisition (SCADA) panels for Room-A/B. Each branch in the power panel has a smart meter for branch-level monitoring. All sensors and actuators deployed in Room-A/B are SCADA slaves communicating with a SCADA master using Modbus TCP protocol. The SCADA master runs on a workstation computer that is located within a conditioned room. Figs. 4(g)-(j) show various sensors deployed in Room-A and Room-B. Note that understanding the air flow field is important for DC monitoring. However, air flow field can only be measured using indirect methods. We deployed air velocity sensors at the vents that supply air to the cold aisle. The air velocity measurements in m/s can be converted to air volume flow rate in m^3/h based on the cross section area of the vents. On the IT racks, we deployed differential pressure sensors to measure the pressure drop across the racks. The pressure drop measurements help understand the spatial distribution of the air volume flows over the cross section of the racks. We also deployed sensors to monitor the concentration of sulfur dioxide (S_2O), hydrogen sulfide (H_2S), and nitrogen dioxide (NO_2), that are often considered the major corrosive gases threatening server hardware. A total of 85 sensors in various modalities were deployed on the testbed. Fig. 4(k) shows an empty private vault provided by Operator-B to be retrofitted as Room-C. Fig. 4(l) shows the four racks that we deployed in Room-C with the constructed cold air containment.

In each server room, we deployed four 42U IT racks. Thus, our testbed of three server rooms hosts a total of 12 racks. The planed power rating for each rack is 5 kW. If all the racks are fully populated with servers, the capital expenditure (Capex) for IT equipment will be twice of the Capex for constructing all the supporting facilities shown in Fig. 4. We received a total of 33 on loan IT devices from four major IT equipment manufacturers as their contributions to this research project. We deployed the same set of 11 IT devices in each server room, as shown in Figs. 4(n) and (o). As the racks are not fully populated, to increase cooling efficiency, we applied blinds as shown in Fig. 4(o) on the empty rack slots. Moreover, to increase the power consumption of the IT racks for realism of the experiments, we deployed four in-rack thermo-fluid simulators in each of Room-A and Room-B, and eight in Room-C, as shown in Fig. 4(n). The thermo-fluid simulator can be configured manually to consume a certain power among multiple discrete levels up to 5 kW. With the thermo-fluid simulators, we can reduce the Capex of the testbed, while maintain its realism in terms of power consumption and heat generation. Thanks to Operator-A's and Operator-B's provision of the spaces as their contributions to the project, the operating expenditure (Opex) of the testbed is mainly the energy charge. The Opex of the testbed over about 1.5 years is about 10% of the Capex for constructing the testbed.

2.3 Configuration of Testbed

We configured all servers and network switches/routers so that we can easily control their operations for experiments. Moreover, as all the three server rooms are located in the premises of Operator-A and Operator-B, it is desirable that we can access all IT equipment and the supporting facilities remotely from our university campus. The remote access should be configured prudently with cybersecurity always in the mind. Although the IT equipment on the testbed will not be used for production, we have a major concern regarding cyber-attacks that take over the SCADA system to damage the costly supporting facilities and/or use the facilities to create safety incidents (e.g., fires by the heater).

We installed the unmodified `CentOS` v6.9 GNU/Linux on all the servers and configured the switches to form an Intranet in a fat tree topology. We configured three routers on our testbed to use three public IPv4 addresses. Once we made our routers publicly accessible, we observed multiple rounds of port scanning from the Internet, which is often the first step of cyber-attacks. We applied a whitelist of accessible ports and remote host IP addresses to restrict the access. The SCADA master provides a password-protected web interface to access real-time or historical sensor data and adjust the setpoints of actuators (heater, supply/exhaust fans, air dampers, and cooling coils). The SCADA master was configured to use HTTPS protocol for the web interface to ensure the integrity and confidentiality of the communications between the testbed and our campus.

We developed a set of `BASH` scripts to control and monitor servers' running status. (1) For CPU status control, we use `cpulimit` v0.2 to maintain the utilization of each physical core of a CPU at a specified level. Then, we use a customized `LINPACK` benchmark provided by the CPU vendor to measure the CPU performance. (2) For hard disk drive (HDD) status control, we use the `cgroups` to maintain the read/write throughput of the HDDs configured to operate in the RAID0 mode. Then, we use `fio` to generate HDD read/write requests. (3) For memory status control, we use `memtester` to generate test traffic and find memory faults. (4) For server status monitoring, we use nine tools: `cpupower`, `edas-utils`, `impitool`, `sar`, `rsyslog`, `smartmontools`, `lm_sensor`, `bmc`, and `fio`. Note that many of these tools are based on the Intelligent Platform Management Interface (IPMI). The collected data traces are uploaded periodically to Google Cloud Storage. During the combined tests of all the scripts we developed, we found that when we tried to maintain the CPU utilization at 100%, IMPI's sampling experienced significant jitters, degrading the quality of the server status monitoring. Thus, in our planed experiments (cf. Section 3.1), the highest CPU utilization that will be maintained for extended period of time is 90%. We only conducted short-period experiments for 100% CPU utilization.

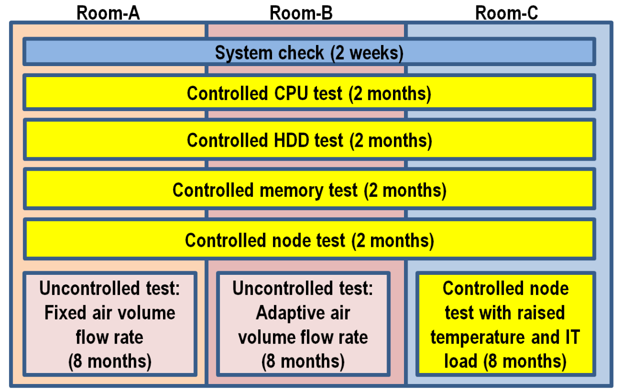


Figure 5: The planed experiments.

On the SCADA master, our contractor used a script language to implement the following algorithms. First, they implemented PID control for the supply and exhaust fans to maintain the air volume flow rate setpoint based on the measurements of the air velocity sensors shown in Fig. 4(i). The control error is within 5%. Second, they implemented bang-bang control for the cooling coil and heater to maintain the temperature of the air supplied to the IT racks at a setpoint. The control error is about 1°C.

In the planed experiments (cf. Section 3.1), the operations of the servers and the supporting facility need to be coordinated. Thus, we configured the NTP clients of the servers and the SCADA master on our testbed to synchronize their clocks with a local pool of NTP servers. The second-accurate clock synchronization of NTP over Internet suffices for the needed coordination.

3 EXPERIMENTS ON THE TESTBED

In this section, we present the design of experiments (Section 3.1), experiences and results of the experiments conducted with the facilities (Section 3.2) and IT equipment (Section 3.3).

3.1 Design of Experiments

We conducted two groups of experiments: controlled tests and uncontrolled tests. Fig. 5 shows the planed experiments. The time periods shown in Fig. 5 are net test times. From our experience, there were also various overheads that consumed the project time, such as preparation of the test scripts, repair of faulty devices, additional tests to verify results, facility maintenance, and etc. We planed to complete all tests shown in Fig. 5 in a duration of 20 months.

A controlled test focuses on a key component of the server, i.e., CPU, hard disk drive (HDD), and memory. Specifically, during a *unit test* of a controlled test, the ambient condition (temperature

Table 1: Experiment settings for controlled experiments.

Parameters	Minimum	Maximum	Step Size
Inlet air temperature	25°C	37°C	1°C
Air flow rate*	2500 m^3/h	12500 m^3/h	2500 m^3/h
Servers' CPU utilization	10%	90%	20%
Hard disk read/write speed	10 MB/sec	100 MB/sec	20 MB/sec
Memory block size	8 kB, 16 kB, 32 kB, 64 kB, 128 kB, 256 kB		

*Applicable for Room-A and Room-B only.

and air volume flow rate) and the operating status of the tested component are maintained at a certain level for one hour. A controlled test consists of hundreds of unit tests with all combinations of the server room ambient condition and server component status each swiping the respective range summarized in Table 1. Note that the maximum temperature setpoint of 37 °C is the record maximum ambient temperature in Singapore. During the controlled node test, we simultaneously vary the operating status of CPU, HDD, and memory. For the first four controlled tests in Room-C, the temperature setpoint for the return hot air is set to be 20°C as suggested by Operator-B. The CRAC unit controls the volume flow rate of the cold air supplied to the four racks. In the last controlled test in Room-C, we vary the temperature setpoint from 21°C to 35°C with step size of 1°C and the total power of eight thermo-fluid simulators within [10 kW, 20 kW, 30 kW, 35 kW]. The controlled tests allow us to understand the performance and thermal safety of the IT equipment under various conditions.

There are two uncontrolled tests in which the air inhaled by Room-A and Room-B are not conditioned by cooling coils and heater. Thus, the servers experience the ambient temperature and RH. In the uncontrolled test in Room-A, we fix the air volume flow rate to a setting that ensures no overheating on the IT racks. This setting is determined from the test results obtained in the controlled tests with the most extreme condition (i.e., 37°C and full utilization of servers). In the uncontrolled test in Room-B, we adapt the air volume flow rate to the outside temperature. The adaptation logic is designed based on the controlled test results. The uncontrolled tests allow us to assess the energy saving that can be achieved by the air free-cooling design in our tropical condition.

3.2 Experiments with Facilities

In this section, we discuss several important issues in operating the supporting facilities and the key measurement results.

3.2.1 Dew point prevention. During the controlled experiments, the cooling coils are used to maintain the cold aisle temperature at the setpoint. When the outside air is hot and humid (e.g., before an afternoon rainfall), the temperature of the cooled air leaving the cooling coil may reach the dew point. In fact, we did see drained water from the cooling coil, which is an indication of 100% RH for the cooled air. As such, the saturated cold air may condense on a colder surface. If such condensation occurs on the printed circuit boards (PCBs) of the IT equipment, the resulted short circuits may damage the IT equipment. Although this concern can be mitigated by the fact that the heat generated by the IT equipment will increase the temperature and thus decrease the RH of the air passing through the IT equipment, for the safety of the IT

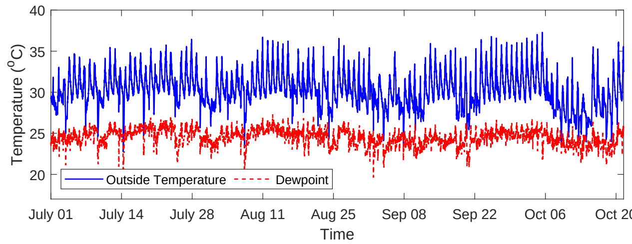


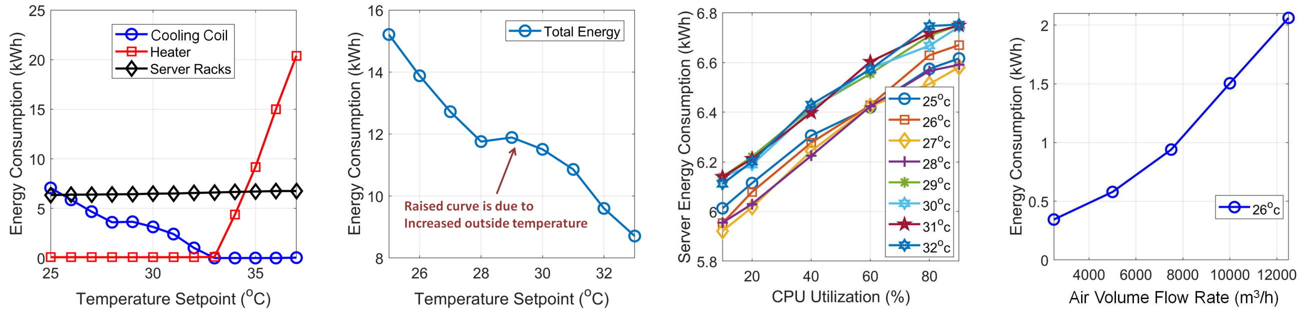
Figure 6: Outside air temperature and dew point in Jul, Aug, Sep, Oct of 2018 in the testbed area.

equipment, we implemented a dew point prevention mechanism in the control algorithms for the cooling coils. Specifically, if the temperature setpoint is more than 3°C lower than the outside air dew point that can be calculated based on outside air temperature and RH, we stop conditioning the inhaled air. Fig. 6 shows the outside temperature and dew point in about four months. We can see that the dew point fluctuates at around 25°C, which is the minimum temperature setpoint during our tests (cf. Table 1). Thus, this dew point prevention mechanism only disallowed the tests with low temperature setpoints for limited time duration. With this mechanism and the heat generated by the IT equipment, the RH at the cold aisle is capped at 90%.

3.2.2 Energy profiles. We conducted a set of experiments to understand the energy consumption profile of Room-A/B. Fig. 7(a) shows the energy consumption of cooling coil, heater, and server racks in Room-A when the temperature setpoint was varied from 25°C to 37°C during a 13-hour experiment. Each data point in the figure is the energy consumption during one hour. When the temperature setpoint was greater than 33°C, the outside temperature was lower than the setpoint. Thus, the cooling coil stopped working and the heater started operation. The energy consumption of the server racks increased by 6% when the temperature setpoint was varied from 25°C to 37°C. This is because the server enclosure's built-in fans rotate faster when the inlet temperature increases. Fig. 7(b) shows the total energy drop of Room-A by about 45% when the temperature setpoint was increased from 25°C to 33°C. This suggests that a significant energy saving can be achieved by air free-cooling. The curve in Fig. 7(b) raises when the temperature setpoint is greater than 29 °C. This is because there was an outside temperature increase after we completed the test with the temperature setpoint of 28 °C.

Fig. 7(c) shows the total server energy consumption in Room-A when the CPU utilization was varied from 10% to 90% and the temperature setpoint was increased from 25°C to 32°C. Each point is the energy measurement over one hour. We can see that, although the server energy in general increases with the temperature setpoint due to the faster server fan rotation, CPU utilization is a major factor affecting the server energy in a linear manner.

Fig. 7(d) shows the energy consumption of the fans in Room-A when the air volume flow rate setpoint was increased from 2500 m^3/h to 12500 m^3/h and the temperature setpoint was fixed at 26 °C. The fans consumed 5.4% to 22.6% of the total energy consumption of Room-A. Our controlled experiments over eight months show



(a) Energy breakdown (b) Total energy (c) Server energy (d) Fan energy

Figure 7: Energy profile of Room-A. The measurements in (a) and (b) were collected during a 13-hour experiment.

that a volume flow rate of $2500\,\mathrm{m}^3/\mathrm{h}$ suffices for each of Room-A and Room-B to prevent overheating.

Fig. 8 shows that PUEs of controlled and uncontrolled tests. Note that in the controlled tests, the heater is activated to maintain the temperature setpoint from 33°C to 37°C. The deployment of the heater is used for our tests only. Therefore, we present the PUEs of the controlled tests with the temperature setpoint lower than 33°C only. In the uncontrolled test in Room A, we fix the air flow rate at $5000\,\mathrm{m}^3/\mathrm{h}$. For the uncontrolled test in Room B, we implemented a control logic that adjusts the air flow rate by controlling the room fan speed such that the maximum outlet temperature of all servers is always maintained below 45°C.

As shown in Fig. 8, the PUEs of the controlled tests are much higher than those of the uncontrolled tests since major energy is consumed by cooling coils and fans to maintain expected setpoints for the temperature and air flow rate. For instance, the PUE can be up to 7.81 when the temperature setpoint is 25°C and the air flow rate setpoint is $12500\,\mathrm{m}^3/\mathrm{h}$. In the controlled tests, the PUE consistently decreases with the cold air temperature. On the other hand, the uncontrolled tests using only fans can greatly reduce the PUE. Specifically, the test with the adaptation logic for controlling the air flow rate can achieve a PUE of 1.05 as shown in Fig. 8. This implies that if the air free-cooling design using fans only is successful, the PUE can be reduced by about 38%, compared to the global average DC PUE of 1.7 [4].

The lowest PUE of 1.05 that we achieved during the uncontrolled tests can be viewed as the lower limit of the PUE for air free-cooled setups. Thus, our experiments provide the baseline understanding of the achievable PUEs in the tropical area. Note that Facebook achieved an annualized PUE of 1.07 by air free-cooling in Oregon. Our results show that a similar PUE can be also achieved in the tropical area.

3.3 Experiments with IT Equipment

This section presents the key results of the server computing performance and reliability from our tests.

3.3.1 *Server performance.*

CPU test results. We measured giga floating point operations per second (GFLOPS) to characterize the CPU performance. We also monitored the CPU core frequency to pinpoint performance degradation caused by frequency throttling. The tests show that, for all

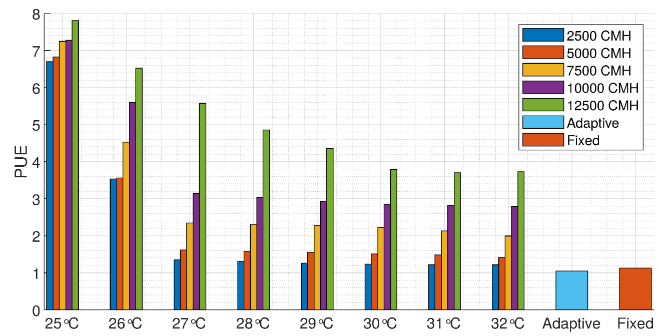


Figure 8: PUEs in controlled and uncontrolled tests. The results with specified temperature setpoints are from the controlled tests; the results labeled "Adaptive" and "Fixed" are from the uncontrolled tests.

CPUs in Room-A and Room-B, the temperature setpoint has little/no impact on GFLOPS and core frequency when (1) the temperature setpoint is from 25°C and 37°C, (2) the CPU utilization is from 10% to 90%, and (3) the air volume flow rate is $2500\,\mathrm{m}^3/\mathrm{h}$ and above. We also investigated the thermal safety of the tested CPUs. The vendor of the tested CPUs specifies $\bar{T}_{\mathrm{case}}$ for each CPU model, which is the upper limit of the CPU *case temperature* for thermal safety. However, each CPU only has a built-in digital thermal sensor to measure T_{core}, which is the *core temperature* on the die. During the tests, the measured T_{core} was always below $\bar{T}_{\mathrm{case}}$. As the case temperature is always lower than the core temperature, the case temperature, although inaccessible, must be lower than $\bar{T}_{\mathrm{case}}$. Thus, all the tested CPUs were thermally safe during the CPU tests in Room-A and Room-B. This also explains the absence of core frequency throttling in the tests. An expert representative from the CPU vendor agreed the above results.

HDD test results. We measured the input/output operations per second (IOPS) and response time during random read and write accesses to characterize the HDD performance. The tests show that, for all HDDs in Room-A and Room-B, the temperature setpoint has little/no impact on IOPS and response time when (1) the temperature setpoint is from 25°C to 37°C, (2) the HDD random read/write speed is from 10 MB/s to 100 MB/s, and (3) the air volume flow rate is from $2500\,\mathrm{m}^3/\mathrm{h}$ to $12500\,\mathrm{m}^3/\mathrm{h}$. The results also show that the HDD random read/write speed has little impact on the server energy consumption.

Memory test results. We measured the speed of copying a large amount of data from a user space memory area to another area using various block sizes to characterize the memory performance. We use cyclic redundancy check (CRC) to verify the integrity of the data copying. The tests show that, for all memories in Room-A and Room-B, the temperature setpoint has little/no impact on memory speed when (1) the temperature setpoint is from 25°C to 37°C, (2) the block size setting is from 8 kB to 256 kB, and (3) the air volume flow rate is from $2500\,\mathrm{m}^3/\mathrm{h}$ to $12500\,\mathrm{m}^3/\mathrm{h}$. No CRC verification errors occurred during the tests. The results also show that the memory speed has little impact on the server energy consumption.

Node test results. We tested the CPU, HDD, and memory simultaneously under a total of six server status levels. At the first level where the server has light workload and the sixth level where the server is stressed, the CPU utilization, HDD read/write speed, and memory block size in data copying are $\{10\%, 10\,\mathrm{MB/s}, 8\,\mathrm{kB}\}$ and $\{90\%, 100\,\mathrm{MB/s}, 256\,\mathrm{kB}\}$, respectively. The test results show that the performance metrics of CPU, HDD, and memory are similar to those tested separately, except that the memory speed is affected by CPU utilization setpoint. This is because CPU cycles are needed to copy data for testing the memory. In contrast, the HDD performance is not affected by CPU utilization setpoint, because HDD is a low-speed devive compared with CPU and memory. All the CPUs were also thermally safe, although CPU, HDD, and memory generate heat simultaneously.

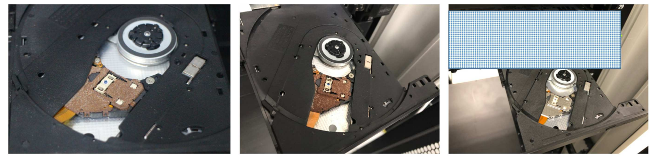
3.3.2 Server Reliability. In controlled and uncontrolled tests, we also measured various reliability data, such as correctable and uncorrectable memory errors, HDDs' latent sector errors and self-monitoring, analysis, and reporting technology (SMART) records to investigate the reliability of the server's hardware during the tests. The measurement results show that all tested HDDs and memories work successfully without any errors during the tests. Moreover, there are no servers -shutdown and overheating when the aisle cold temperature setpoint is up to 37°C and the CPU is fully utilized. However, we observed serval server faults on the testbed during the tests. The detailed analysis of the faults will be presented in next section.

4 IT EQUIPMENT FAILURES

In this section, we first describe a summary of IT equipment failures that occurred on the testbed during the tests. Then, we present our investigation on the reason of the failures.

4.1 Summary of Failures

The testbed has a total of 18 servers from four different vendors which are deployed in three server rooms. During the tests, a number of servers in Room-A and Room-B had faults and could not be booted. Specifically, among 12 servers from the same Vendor 1 in Room A and Room B, six of them failed after about 6 months from the initial operation. We requested the Vendor 1 to perform on-site examination for the faulty servers. They found that the fan backplane of all failed servers and the motherboards of three servers



Room A Jan 4th 2019 | Room A Sep 27th 2019 | Room C Sep 27th 2019

Figure 9: Corrosion observed on the compact disk (CD) drive of a server in Room A. The rightmost figure shows the CD drive of the same model of server in Room C.

are malfunctioned. The CPU on one of the servers with the malfunctioned mainboard is damaged. Vendor 1 replaced the malfunctioned components to revive the servers. Then, after 6 months from the first repair, four of six fixed servers from Vendor 1 failed again.

In addition, we encountered two server faults from Vendor 3 in Room A and Room B after 11 months from their initial operations. Severe corrosion can be observed on the compact disk drives of the two failed Vendor 3 servers, as shown in Fig. 9. Note that all failures occurred on several servers from the same vendors. The remaining servers from other Vendors and all network equipment, forming a large portion of all tested IT equipment, are still healthy after 18-month operation.

4.2 Investigation on Failure Reason

Vendors performed lab-based fault analysis on the faulty server components. We also investigated the server room condition to find the reasons of the server faults. In what follows, we provide detailed information of the vendors' fault analysis and our investigation.

4.2.1 Vendor's fault analysis. The vendor found that the faults of the mainboards and fan backplane were caused by dusts and/or corrosion on the PCBs. We used a microscope to examine the PCBs of the motherboards of the faulty servers. We can see dusts resting on the PCBs. The faulty motherboards functioned normally at room temperature in the lab. But the fault could be reproduced after liquid nitrogen was sprayed on the motherboard, suggesting that the fault was caused by dust. This is because when the moisture in the air condenses on the motherboard, the dust on the motherboard absorbs the condensed moisture and causes short circuits. After cleaning the motherboard using liquid, the motherboard restored and survived liquid nitrogen spray tests. The vendor also confirmed that high temperature is not the cause of the server failures. A faulty CPU is caused by the over voltage due to a failed power supply chip on the mainboard. In other words, the CPU failure is a cascading failure, which is not caused by overheating.

In summary, the vendor's fault analysis results show that (1) corrosion caused by airborne contaminants on the motherboards and other supporting PCBs is the main reason of the faults; (2) the server faults are not caused by CPUs, HDDs, and memories; and (3) high temperature is not a reason of the server faults.

4.2.2 Our investigation. We investigated the following aspects on the potential reasons of the server failures.

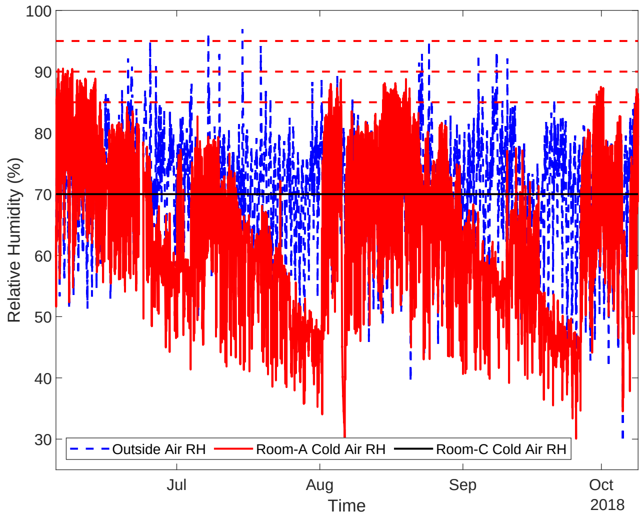


Figure 10: RH of outside air, cold air in Room-A, and cold air in Room-C before the server faults in Room-A/B. The three horizontal dash lines represent the servers' maximum allowable RH levels specified in their datasheets.

Temperature. The faulty servers are compliant with ASHRAE's A3 or A4 requirement, i.e., they can operate reliably under inlet temperature of 40°C or 45°C. As the maximum cold aisle temperature was 37°C during the tests, this double confirms that the high temperature is not the reason of the faults.

RH. From the servers' datasheets, each server requires that the RH is lower than a threshold among 85%, 90%, and 95%. Fig. 10 shows the traces of outside air RH and the cold air RH in Room-A during three months before the server faults occurred. Note that because we varied the cold air temperature in Room-A during the controlled experiments, the cold air RH changed accordingly as shown in Fig. 10. We can see that the most stringent RH requirement of 85% was violated for limited time periods, while the other two RH requirements of 90% and 100% were never violated. As a comparison, we also investigated the cold air RH in Room-C. Following the common practice, Operator-B sets 20°C and 50% as the temperature and RH setpoints for the hot return air that is inhaled by the CRAC unit. The temperature and RH within the cold air containment is about 17°C and 70% that is represented by the solid horizontal line in Fig. 10. From the figure, we can see that, in fact, the RH of the cold air of Room-C is close to and higher than the average RHs of Room-A's outside and cold air, respectively. Since there is no fault in Room-C, we think high RH alone is not the reason of the faults.

Corrosive gases. We investigated the measurements of the corrosive gases concentration. Table 2 shows a server vendor's requirements and measurements by gaseous sensors deployed in the testbed. We can see that the SO_2 concentration is slightly higher than the requirement and the NO_2 concentration is up to 5x higher than the requirement. Since the gas sensors we deployed on the testbed as shown in Fig. 4(i) are designed for real-time long-term monitoring but with less accuracy, we contracted a third-party company with gaseous contaminants monitoring expertise to perform one-day measurements in Room-A and Room-C simultaneously. Fig. 11 shows the company's measurement apparatuses in the two rooms. Table 3 shows the measurement results. We can see that the NO_2 concentration in Room-A is at least 4.9x higher than that in Room-C. As Room-A and Room-B are about 100 meters from a major highway in our area, we also suspect that the car exhaust gas is a major source of the NO_2. Room-C has clean air because DC operators filtrate the air entering the DC building to remove the corrosive gases.

Table 2: A server vendor's requirement and our measurement (unit: ppb).

Gas	Required*	Measured
H_2S	< 3	≈ 0
SO_2	< 10	≈ 15
NO_2	< 50	100-250

*The concentration upper bounds are based on RH $\leq 50\%$.

Table 3: Simultaneous precise one-day measurement (unit: $\mu g/m^3$).

Gas	Room-A	Room-C
H_2S	13	< 12
SO_2	< 10	< 10
NO_2	49	< 10

"$<$" means that the actual value is below the measurement resolution.

Summary and discussion. From an existing study [11], corrosion on metal materials is a joint effect of corrosive gases and RH, because the corrosive gases will absorb moisture in the air to form acids. Particulate contaminants can also attack the metal materials in a similar way or cause short circuit if the ambient RH exceeds the deliquescent RH of the contaminants [1]. Note that dust can be seen on the faulty motherboards under microscope during the server vendors' lab-based fault analysis. Therefore, the server faults in Room-A and Room-B can be attributed to (1) the co-presence of NO_2, dust, and high RH, (2) the lack of anti-corrosion coating for the PCBs in the faulty servers.

Note that Room-A and Room-B are about three kilometers from the coastline. ASHRAE's whitepaper [1] mentions that sea salt carried by winds can also damage electronic devices in coastal areas. As there are no mature off-the-shelf sensors to monitor salt concentration in the air, our current research falls short of telling whether sea salt contributed to the server faults. But this issue is of great interest for future research.

5 LEARNED LESSONS AND DISCUSSIONS

As the first systematic trial of real air free-cooling for DCs in the tropics, our research has generated various valuable experiences and information for DC-related entities. Some of them are in the form of learned lessons that the future research and industrial practice should consider. The lessons are summarized as follows.

Temperatures up to 37°C do not impede the air free-cooling. Our experiment results based on the testbed show that the servers can operate without computing performance degradation under the cold aisle temperature up to 37°C. The investigation shows that the server faults on our testbed were not caused by temperature. Moreover, many latest servers are compliant with the ASHRAE A3 requirement to be able to tolerate 40°C. Thus, the tropics' air

(a) Room-A (b) Room-C

Figure 11: Simultaneous precise one-day measurement of corrosive gases concentrations in Room-A and Room-C. The measurement results are shown in Table 3.

temperatures in our area with a record maximum of 37°C will not impede the air free-cooling.

Server hardening vs. airborne contaminants removal. We believe that by only deploying hardened IT equipment with anti-corrosion coating on the PCBs exposed to air, hardware faults caused by corrosion and conductive dust will be resolved. Alternatively, better airborne contaminants filtration can be employed. The following two categories of filtration approaches can be considered:

- **Passive filtration** This project uses Class MERV-6 to remove PM10 and larger particles. Filters in higher classes can be used instead to remove finer particles. For corrosive gases, the hot air generated by the servers can be recirculated and mixed with the outside cold air to form warm air with lower RH to be supplied to the servers. The lower RH will reduce the corrosive gases' attack capabilities. This approach requires no extra energy and exploits the higher temperature tolerance of the latest servers. The details of this approach are described in [12]. The speed control logic of server built-in fans may need adjustment to avoid fast wear and tear due to unnecessarily high rotation speeds in high temperatures. Note that the server fan speed control logic update can be implemented using a shell script and deployed easily.
- **Active filtration** Electrostatic air cleaners can be employed to strengthen the particle removal. Traditional chemical approaches can be applied to remove corrosive gases. However, these approaches will consume energy.

This project narrowed the feasibility problem of air free-cooling in the tropics down to the effectiveness of airborne contaminants removal and its associated Capex and Opex. The choice of server hardening and better filtration is a design problem that will depend on specific configurations and constraints of the DC. For example, server hardening may not be feasible for colocation DCs. We note that carefully choosing the location for cleaner ambient air may significantly ease the design of an air free-cooled DC.

Implication on existing DCs. Our results also suggest that the existing DCs operated in enclosed buildings can consider increasing their temperature setpoints for better energy efficiency if sufficient air flows are provided to the servers to take away generated heat and avoid hot spots. These DCs will not have the airborne contamination problem, owing to the enclosed design and the deployed air filtration systems.

6 CONCLUSION

In this paper, we describe the design, construction, and configuration of an air free-cooled DC testbed in the tropical condition. We also present the key results of the experiments conducted on the testbed, including the energy efficiency of the air free-cooling facility, servers' computing performance, server faults during the experiments, and the investigations on the reasons of the faults. The experiences and learned lessons discussed in this paper will be useful to future efforts of building and operating air free-cooled DCs in the tropics and beyond, aiming at increasing the DC energy efficiency while not compromising the server performance and reliability.

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