IPP HURRAY!

www.hurray.isep.ipp.pt

Technical Report

Building a Microscope for the Data Center

Nuno Pereira
Stefano Tennina
Eduardo Tovar

HURRAY-TR-120704
Version:
Date: 7/4/2012

Building a Microscope for the Data Center

Nuno Pereira, Stefano Tennina, Eduardo Tovar

IPP-HURRAY!

Polytechnic Institute of Porto (ISEP-IPP)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8340509

E-mail: nap@isep.ipp.pt, sota@isep.ipp.pt, emt@dei.isep.ipp.pt

http://www.hurray.isep.ipp.pt

Abstract

Managing the physical and compute infrastructure of a large data center is an embodiment of a Cyber-Physical System (CPS). The physical parameters of the data center (such as power, temperature, pressure, humidity) are tightly coupled with computations, even more so in upcoming data centers, where the location of workloads can vary substantially due, for example, to workloads being moved in a cloud infrastructure hosted in the data center. In this paper, we describe a data collection and distribution architecture that enables gathering physical parameters of a large data center at a very high temporal and spatial resolutionof the sensor measurements. We think this is an important characteristic to enable more accurate heat-flow models of the data center andwith them, _and opportunities to optimize energy consumption. Havinga high resolution picture of the data center conditions, also enables minimizing local hotspots, perform more accurate predictive maintenance (pending failures in cooling and other infrastructure equipment can be more promptly detected) and more accurate billing. We detail this architecture and define the structure of the underlying messaging system that is used to collect and distribute the data. Finally, we show the results of a preliminary study of a typical data center radio environment.

Building a Microscope for the Data Center

Nuno Pereira, Stefano Tennina, Eduardo Tovar

CISTER/INESC-TEC, ISEP, Polytechnic Institute of Porto, Porto, Portugal,
`nap@isep.ipp.pt, sota@isep.ipp.pt, emt@isep.ipp.pt`

Abstract. Managing the physical and compute infrastructure of a large data center is an embodiment of a Cyber-Physical System (CPS). The physical parameters of the data center (such as power, temperature, pressure, humidity) are tightly coupled with computations, even more so in upcoming data centers, where the location of workloads can vary substantially due, for example, to workloads being moved in a cloud infrastructure hosted in the data center. In this paper, we describe a data collection and distribution architecture that enables gathering physical parameters of a large data center at a very high temporal and spatial resolution of the sensor measurements. We think this is an important characteristic to enable more accurate heat-flow models of the data center and with them, find opportunities to optimize energy consumption. Having a high resolution picture of the data center conditions, also enables minimizing local hotspots, perform more accurate predictive maintenance (pending failures in cooling and other infrastructure equipment can be more promptly detected) and more accurate billing. We detail this architecture and define the structure of the underlying messaging system that is used to collect and distribute the data. Finally, we show the results of a preliminary study of a typical data center radio environment.

1 Introduction

Data centers are a central piece of today's Internet infrastructure and have become critical for many medium and large organizations. A data center is a facility (one or more rooms, floors or buildings) custom built to house large computing systems, including networking, storage systems and also power distribution and cooling.

The operation of a data center is an instantiation of a Cyber-Physical System (CPS) in the sense that it requires managing physical parameters, such as power and environmental variables of the data center (e.g., temperature, humidity, pressure), that are coupled with computations. This is especially true in future data centers, where we can expect that management of cloud-related workload will be performed more aggressively. This workload management includes distributing or consolidating workloads throughout data center machines, and this impacts physical parameters (power and environmental) of the data center in a very dynamic manner.

This paper reports the progress being developed towards energy-efficient operations and the integrated management of cyber and physical aspects of data centers. We are developing an integrated system composed by wired and wireless sensors which monitor power consumptions of the servers and environmental conditions, with the goal of achieving an overall reduction of data centers' energy consumptions. The architecture we propose here is intended to be hierarchical, modular and flexible enough to achieve high temporal and spatial resolution of the sensor measurements, with negligible latencies of sensors' reports to the data center management control station.

Overall, the advantage of having fine-grained power and environmental measurements in this application scenario is twofold: (i) measuring the power consumption at the single server level has enormous benefits for the business logic of data centers' owners, since they can offer services and billing to their customers based on the actual consumption[1], and (ii) although there are in literature models to predict heat-flows used in commercial Computer Room Air Cooling ($CRAC$) systems, those models often lack of spatial resolution, so the availability of micro-climate conditions would help improving those models as well as continue feeding them with real data will improve the reliability and accuracy of their forecasts.

Fine-grained measurements are also the basis to provide different views of the system, each of them customized to different users. Our architecture allows to set the desired resolution of the readings upon user's requests, for example to investigate some problems in a specific area (row, room or floor) of the data center building. Every single sensor can be configured by setting user defined alarms and trigger measurements reports adaptively, by changing or (re-)configuring specific thresholds at run-time.

In this paper, we describe the data collection and distribution architecture. We will detail how the environmental and power data will be collected from the data center and initial deployment experiments. The remaining of this paper is organized as follows. Section 2 describes related work in the same topic of monitoring data center conditions. Section 3 overviews our proposed hierarchical and modular system architecture by focusing on its data gathering part, while Section 4 presents the way data collected are exposed to the end users using the publish-subscriber paradigm. Section 5 deals with preliminary results on wireless sensor network (WSN) deployment we did in a real data center in Lisbon, Portugal, in November 2011. Section 6 concludes this paper with an overview on the on-going future work.

2 Related Work

Thermal management and green data centers have received considerable attention in recent research literature. Two main approaches can be identified: mechanical design-based and software-based [1]. The former approaches aim at studying the airflow models, data centers layout and cooling system design in order to optimize the location of the racks and CRAC units. On the other hand,

---

[1] This project is being carried out in conjuntion with a medium/large service provider in the area (Portugal Telecom), which defined this as an important goal of the system

the latter approaches focus on minimizing the cooling costs by distributing or migrating jobs among the servers. The result of this study is the design of thermal-aware scheduling mechanism to distribute the workload where the power budget (i.e., the product of power and temperature [2]) is more favorable. However, in the current data center thermal management systems, the mechanical- and software-based approaches are usually independent on each other [1].

A closely related problem, power management in data centers, has been an important concern for some time now [3–7]. Dynamic voltage scaling [3, 5] in QoS-enabled web-servers can minimize energy consumption subject to service delay constraints. On/off power management schemes [4–7] have also been studied in the context of data centers.

Few very recent approaches rely on building software models through a joint coordination of cooling and load management [8, 9]. However, the complexity of data center airflow and heat transfer is compounded by each data center facility having its own unique layout, so achieving a general model is difficult [10]. In fact, in [8], authors stress that their model has several parameters that need to be determined for specific applications. Then, acquiring data at a fine enough resolution to validate models is a considerable undertaking and current research issue concerning the type and placement of sensors need to be addressed [10].

Along this line, some recent work [11, 12] pushed in the direction of deploying wireless sensor nodes and monitor the thermal distribution, to figure out how to avoid hot-spots and overheating conditions. In [12], for example, 108 wireless sensor nodes were deployed in a floor of the IBM data center in Geneva. We differ from these works in the sense that we want very fine-grained (in space and time) gathering of power and environmental parameters and including other physical quantities other than only temperature. Our goal is also to build a representation of the data center through which administrators and designers can rigorously identify problems and solutions.

Our approach has similarities to [1], where authors propose a (proactive) thermal management system built upon an air flux mathematical model, which leads to a formulation of a minimization of cooling energy problem. Moreover, in [13], the same authors developed a joint communication and coordination scheme that enables self-organization of a network of external heterogeneous sensors (thermal cameras, scalar temperature and humidity sensors, airflow meters) into a multi-tier sensing infrastructure capable of real-time data center monitoring. Differently from [1, 13], our proposed system is based on a hierarchical, modular, flexible and fine-grained sensor network architecture, where data collected from heterogeneous sensors (including power data) and the analysis of their inter-correlations will enable closer examination and a better understanding of the flow and temperature dynamics within each data center [14]. To our knowledge, no previous work enables correlating power and environment characteristics on a per rack or per-server granularity.

Multiple long-wavelength infrared image sensors can be used to capture thermal maps of an environment [15]. While thermal cameras are an interesting approach, we find that they suffer from several practical issues: (i) the current cost of thermal cameras is substantial, and, due to field-of-view limitations (data centers are typically organized in narrows rows), a high number of them can be required to cover a data center; (ii) mapping the view of the camera with the infrastructure being monitored is more challenging than with point sensors, and it is especially difficult to manage when changes are made to the layout of the data center (e.g., addition/removal of servers and racks). However, as in [13], our system has provisions to support thermal image sensors as a smart sensor that can provide point temperature readings with a configurable resolution.

The data collection and distribution architecture described in this paper builds upon previous work in SensorAndrew [16], which defined an Internet-scale infrastructure for sensing and actuation, using the XMPP protocol (more details about XMPP are given later) at its core, providing both point-to-point and publish-subscribe communication, confidentiality, access control, registration, discovery, event logging and management of sensor/actuator devices.

There are a number of other efforts, which address some of these functionalities. The MQ Telemetry Transport (MQTT) [17] is a publish-subscribe messaging protocol, designed for constrained devices. While it is very lightweight and as been successfully applied in several areas [18–20], it does not provide any flexible mechanism to define messaging format and has also no built-in security features. The Global Sensor Networks (GSN) [21] supports the flexible integration and discovery of sensor networks and sensor data. It is a service-oriented architecture, where sensors can be accessed using SQL queries and web services. GSN is substantially single-application centric and does not support security features. Pachube [22] recently gained increased visibility with its real-time data collection infrastructure that enables sensor-derived data to be distributed at Internet scale. Pachube, however, focuses on much larger time scales for the data collection than we are interested in.

3 Architecture Overview

The architecture of our system can be divided into three main sections. (i) The data-producing entities such as the sensor networks, which gather environmental data, IT equipment or building equipment, which gather the data from the environment, and also power consumption data. The data from these sensor networks is delivered to a (ii) data distribution system that acts as a broker between the (iii) data producing entities and the consuming applications (e.g., logger applications, alarm monitor, user interface applications).

At the core of the architecture depicted in Figure 1 there is a data distribution middleware, which will take care of handling the data coming from different sources such as the environmental and power sensors and deliver this data to the applications interested in this data. The applications can be a data logger that gathers historical information, visualization tools, alarms monitors or any other application that can be developed in the future.

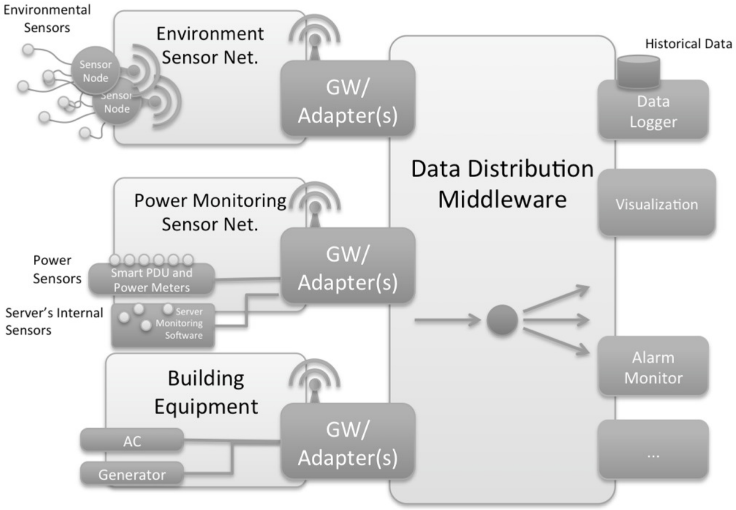


Fig. 1. Architecture Overview

In the following subsections, our proposed system architecture will be described in more detail, highlighting each component of the data gathering and data distribution system.

3.1 Environment and Power Data Collection

In order to trade-off among (i) fine-grained sensors' measurement (spatial) resolution, (ii) system flexibility and modularity and (iii) low-latency reporting of the measurements, the proposed architecture for the data collection is a mix of wired and wireless technologies.

The WSN is a stacked multi-tier architecture, where each level represents a network tier with the corresponding devices and communication technology used. The lower level, *level-0* consists of sensor nodes, i.e., computational units with several physical sensors attached, which perform sensing tasks and deliver data to the devices at the next level in the hierarchy through a wired bus. At *level-1*, cluster heads are responsible for querying the sensor nodes within their respective cluster. A cluster is composed by one cluster head (bus master) and several sensor nodes (bus slaves) attached to the wired bus. Then, these cluster heads are responsible for data aggregation and sensor fusion. They communicate using IEEE 802.15.4 with devices at the next level in the hierarchy. At the *level-2* of the network hierarchy, (environment) gateways are present. These devices have the highest computational capabilities among the devices present in the sensor network field. Gateways provide the data gathered from the sensor network to the data distribution system in a standard format. Finally, in *level-3*, the data distribution provides means to deliver the data gathered from the sensor network to the applications. The data distribution system supports any number of gateways and applications in a distributed and transparent way.

Sensor Nodes: starting from the bottom of the network architecture, a Sensor Node is a communication/computation enabled device physically linked (e.g., over a I2C bus) to a given number of sensors. These sensors are responsible for measuring different physical parameters like, e.g., temperature, humidity, pressure, as well as several power sensors to monitor the power consumption of each server in the rack.

To keep the complexity low, at this tier of the Network Architecture, the Sensor Nodes communicate with one Cluster Head over a bus, e.g., using a RS485/MODBUS technology [23]. In particular, the Cluster Head node acts as a local coordinator and master of the bus. The sensor nodes are deployed one each rack and their sensors get measurements from all the elements of the rack.

Cluster Heads: the Clusters will be connected with each other in a ZigBee/IEEE802.15.4 mesh topology to form a WSN Patch, where a common Gateway is in charge of gathering data and sending them over long range communication technology (e.g., WiFi). In terms of HW platforms, the Cluster Head node will be the same platform as a generic Sensor Node, with an on-board ZigBee radio.

Gateways: the sensor network can have one or more Gateways. Gateways maintain representations of the data flows from the sensor network to the data distribution system. They perform the necessary adaptation of the data received from the WSN. The gateways can be deployed as one per room serving all the rows of racks in that room; more gateways can also be deployed to improve radio coverage, for load-balancing or for redundancy.

3.2 Data Distribution

The data distribution middleware is a central part of the proposed architecture. This system is in charge of distributing the data from the source to the interested applications. We leverage on the previous experience of SensorAndrew [16] and employ the eXtensible Messaging and Presence Protocol (XMPP) [24] as the core protocol for managing sensor data collection and distribution. In this architecture, sensors (and actuators) are modeled as XMPP event nodes in a push-based publish-subscribe architecture. The loosely coupling between publisher and subscribers allows a higher scalability and more dynamism in the network topology. Moreover, this architecture supports the following features [16, 24]: (i) standard messaging protocol; (ii) extensible message types; (iii) point-to-point and multicast messaging; (iv) data tracking and/or event logging; (v) security, privacy and access control; (vi) registration and discovery services (vii) redundancy and Internet-scale.

The XMPP [24] is the basis for the messaging of our system. XMPP is an open-standard communications protocol for message-oriented middleware based on Extensible Markup Language (XML). Unlike most instant messaging protocols, XMPP uses an open systems approach of development and application, by which anyone may implement an XMPP service and interoperate with other organizations' implementations. The architecture of an XMPP network is run in a fully distributed fashion, i.e., there is no central master server. XMPP has extensions for several models, including one-to-one communication and publish-subscribe model, and can be location-aware. It has built-in authentication with support for secure channels (SSL and TLS) and supports storage of messages for later delivery. XMPP applications include network management, content syndication, collaboration tools, file sharing, gaming, and remote systems monitoring. Finally, XMPP is implemented by a large number of clients, servers, and code libraries, and most of this software is distributed as free and open source.

4 Mapping The World

We have defined a hierarchy, adapted to the environment of a data center, that structures the messaging system. As we will describe in this section, this hierarchy reduces the number of data items (event nodes) that a user application needs to subscribe to and also allows for the user applications to zoom-in the data center in a flexible manner.

The hierarchy is defined through an XML schema that models the world. This model includes 3D geographical and logical information of all elements, including sensors, servers, racks, rooms and even buildings or cities. The model includes hierarchical links: servers can be placed *logically* inside a room, racks can be placed inside a room, and a room can be connected to a building and so on. The logical organization makes it simpler to organize the hierarchy without depending on the geographical / 3D information of the model. These levels in a data center context are shown in Figure 2. This is a logical hierarchy reflected on the XMPP event nodes, which lives in the XMPP servers. In this way, this hierarchy can be replicated and load-balanced by using the common mechanisms implemented by the XMPP server.

With this hierarchical arrangement, for example, when an administrator wants to have data from a given room, the user application only needs to subscribe to that room and automatically he will be subscribed to all the sensors in that room. This could however result in a single client subscribing to a large number of event nodes, which can be a problem for clients with limited processing, memory and battery life capacities, such as, e.g., a mobile phone.

To address this issue, we took advantage of the fact that our messaging system can have XMPP event nodes which are direct representations of physical nodes (e.g., a real sensor node on a rack), but it can also have XMPP event nodes which can represent a category or a set of nodes with some common logical characteristics (e.g., belonging to a given room). In this way, a room might have a representation in the messaging system as a virtual logical XMPP node, and, for example, the temperature values of a room will be published as a trace over time of the aggregated (e.g., average, minimum or maximum) values of all the measurements from the sensor nodes belonging to that room, while all those readings will be published on virtual physical XMPP nodes to be

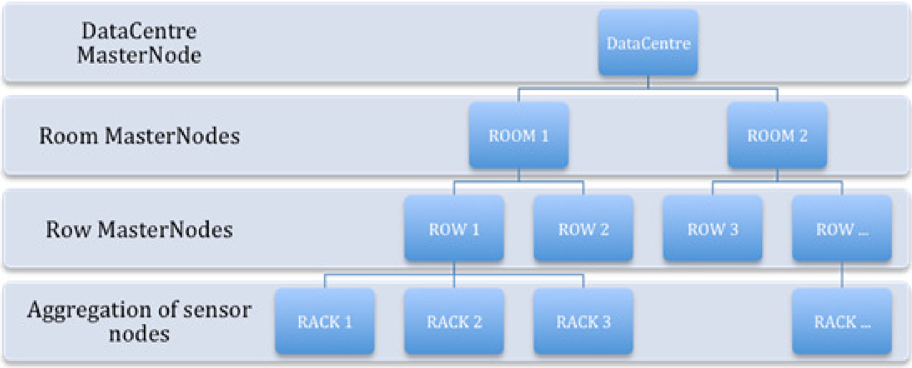


Fig. 2. Hierarchy of the nodes.

available later for different views. Figure 3 represents a possible configuration of this mechanism.

It is important to note that this architecture supports several clients. For example, we can simultaneously have the following: (i) a logger application that subscribes to all nodes and simply logs all the data; (ii) an application that subscribes to specific events nodes that deliver alarm notifications; (iii) an application that is only interested in the data for a particular row of the data center; (iv) an application that, for management and configuration purposes, only needs to know when a new device is added to the system; (v) an application that is only interested in power readings. We also built a graphical user interface (GUI) application that can run in both desktops and mobile devices that provides an overview of the data center conditions. It is a simple and clean interface that gathers all relevant data, allowing the user to navigate trough a representation of the data center and observe the data collected.

5 The Data Center Radio Environment

This section presents a first step toward enabling a large installation of wireless communicating devices. It is often assumed that the presence of lots of metallic surfaces (such as racks) and power cables suspended on the ceiling, makes a data center room a harsh environment in terms of radio signal propagation. Therefore, we conducted an analysis of the radio conditions of a typical data center, to assess the validity of that assumption and evaluate its impact. The measurements were performed in a data center (located in Lisbon, Portugal) owned by the largest

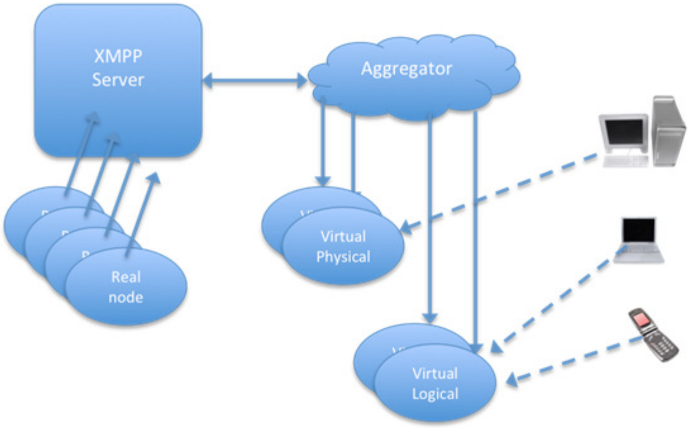


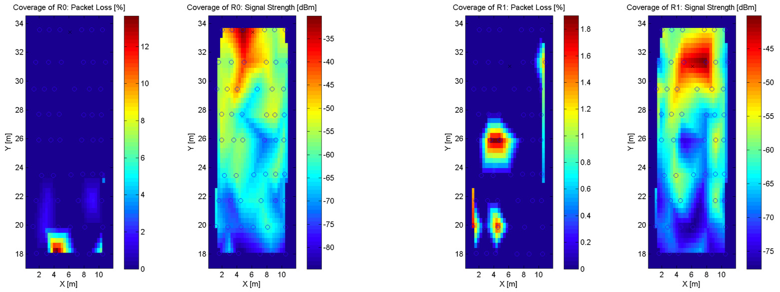
Fig. 3. Node Distribution Proposal.

Portuguese telecommunications operator, Portugal Telecom (PT), which also provides hosting and cloud-based services. The objective of such measurement campaign has been twofold: (i) evaluate the available IEEE 802.15.4 channels for the monitoring network to be deployed in the data center, and (ii) test the connectivity among IEEE 802.15.4 radios in the field, in order to identify the requirements for the formation of the network topology.

Background Noise: We first acquired the background noise level, i.e., the possible interference on the monitoring network due to external IEEE 802.11/WLANs. To do this, we used a frequency spectrum analyzer [25]. As expected, we observed that there are only few IEEE 802.15.4 channel in the 2.4 GHz band available. Channel 26, as it shown a negligible interference from 802.11, was the preferred channel for our measurements. In general, these background noise measurements show that the number of available channels in a typical data center might be low.

WSN Connectivity: For the connectivity measurements, we used 9 TelosB [26] nodes (a GW and 8 routers) running on batteries and 3 TelosB power by USB, acting as sniffers. The routers were placed at the top of the center rack of 9 rows on a data center.

First, we checked the connectivity between routers. For this, we placed the GW on a corner of the data center and the routers (R1-R8) were left on the center of the rows. This experiment tested that the chain among the GW and all the routers was working, i.e., the GW started emitting beacons, R1 gets these beacons, associates to the GW and start emitting its own beacons. Then R2 gets R1's beacons, associates with R1 and starts emitting its own beacons, and so on until R8. At run time, all routers were able to emit non-interfering beacons, on a time-division fashion.



(a) Coverage of GW (R0). Left: packet loss. Right: RSS.

(b) Coverage of R1. Left: packet loss. Right: RSS.

Fig. 4. Data Center Room Radio Measurements

Then, we started taking measurements with the 3 sniffer nodes as follows. First, we placed the 3 nodes on one half of the row and then on the other half of the row (the 3 nodes were spaced about 1.5 meters from each other, where the one furthest from the middle was 5 meters from the center), then we collected packets for 5 minutes in each half section of the row and repeated this procedure for 9 rows.

The measurements were performed by looking at a counter in the beacon payload that was incremented each time a beacon was transmitted. By extracting the source address and the counter in the beacons from the sniffers' logs we could measure the packet loss probability on each measurement point and with respect to each router, as well as information about the Received Signal Strength (RSS) of each received packet. By combining these data, it was possible to build maps of the coverage for each beacon emitter. Figure 4 shows such results for the GW and the cluster head R1. The packet loss is better than what one could have expected: in general the majority of the routers was able to cover half of the room with negligible losses (i.e., $packetloss < 2\%$). Only spots of connectivity loss areas were evidenced, e.g., in proximity of a pillar in the room: these conditions can be resolved by planning accurately the position of the routers (cluster heads).

6 Conclusion

Instrumenting data centers with very fine spatial and temporal granularity has a twofold advantage in terms of business logic of data centers owners and have a better control on the micro-climate conditions in the rooms.

We have defined an efficient, hierarchical and modular system architecture, and we are developing specialized hardware to enable it. Moreover, we made a study on the radio performance in a real data center. This study enabled us to understand better the radio conditions. Our findings confirm reports by previous work [11, 12]: even in a data center room of reasonable dimensions, each wireless node could interfere with up to 65% of the nodes. Then, having too many nodes interfering with each other is an obstacle towards gathering sensor readings with high temporal resolution, and this needs to be considered in our design.

Overall, we believe that our architecture, which mixes wired and wireless technologies in a modular and flexible fashion, enables interesting trade-offs between fine-grained monitoring and low-latency.

Acknowledgement

We would like to acknowledge (in alphabetical order) the help by Bruno Saraiva, João Loureiro, Manuel Santos, and Ricardo Severino during the implementation of this work. This work was supported by the SENODS project, ref. SENODS - FCOMP-01-0124-FEDER-012988, co-funded by National Funds through the FCT-MCTES (Portuguese Foundation for Science and Technology) and by ERDF (European Regional Development Fund) through COMPETE (Operational Programme 'Thematic Factors of Competitiveness'), the CMU-PT Program, by National Funds through the FCT-MCTES (Portuguese Foundation for Science and Technology), under the Carnegie Mellon Portugal Program with Grant ref. FCT-CMU-PT/0012/2006 and the NoE CONET, funded by the European Commission, with grant nr. FP7-ICT-224053.

References

1. E. K. Lee, I. S. Kulkarni, D. Pompili, and M. Parashar. Proactive thermal management in green datacenters. *Journal of Supercomputing (Springer)*, 51(1):1–31, June 2010.
2. Taliver Heath, Ana Paula Centeno, Pradeep George, Luiz Ramos, Yogesh Jaluria, and Ricardo Bianchini. Mercury and freon: temperature emulation and management for server systems. *SIGOPS Oper. Syst. Rev.*, 40(5):106–116, October 2006.
3. Pat Bohrer, Elmootazbellah N. Elnozahy, Tom Keller, Michael Kistler, Charles Lefurgy, Chandler McDowell, and Ram Rajamony. Power aware computing. chapter The case for power management in web servers, pages 261–289. Kluwer Academic Publishers, Norwell, MA, USA, 2002.
4. Ruibin Xu, Dakai Zhu, Cosmin Rusu, Rami Melhem, and Daniel Mossé. Energy-efficient policies for embedded clusters. In *Proceedings of the 2005 ACM SIGPLAN/SIGBED conference on Languages, compilers, and tools for embedded systems*, LCTES '05, pages 1–10, New York, NY, USA, 2005. ACM.
5. Tibor Horvath, Tarek Abdelzaher, Kevin Skadron, and Xue Liu. Dynamic voltage scaling in multitier web servers with end-to-end delay control. *IEEE Trans. Comput.*, 56(4):444–458, April 2007.
6. David Meisner, Brian T. Gold, and Thomas F. Wenisch. Powernap: eliminating server idle power. In *Proceedings of the 14th international conference on Architectural support for programming languages and operating systems*, ASPLOS '09, pages 205–216, New York, NY, USA, 2009. ACM.
7. Shengquan Wang, Jian-Jia Chen, Jun Liu, and Xue Liu. Power saving design for servers under response time constraint. In *Proceedings of the 2010 22nd Euromicro Conference on Real-Time Systems*, ECRTS '10, pages 123–132, Washington, DC, USA, 2010. IEEE Computer Society.

8. Luca Parolini, Bruno Sinopoli, and Bruce H. Krogh. Reducing data center energy consumption via coordinated cooling and load management. In *Proceedings of the 2008 conference on Power aware computing and systems*, HotPower'08, pages 14–14, Berkeley, CA, USA, 2008. USENIX Association.
9. Rongliang Zhou, Zhikui Wang, Cullen E. Bash, and Alan McReynolds. Data center cooling management and analysis – a model based approach. In *28 Annual Semiconductor Thermal Measurement, Modeling and Management Symposium (SEMI-THERM 2012)*, San Jose, California, USA, March 2012.
10. Jeffrey Rambo and Yogendra Joshi. Modeling of data center airflow and heat transfer: State of the art and future trends. *Distrib. Parallel Databases*, 21(2-3):193–225, June 2007.
11. Chieh-Jan Mike Liang, Jie Liu, Liqian Luo, Andreas Terzis, and Feng Zhao. Racnet: a high-fidelity data center sensing network. In *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems*, SenSys '09, pages 15–28, New York, NY, USA, 2009. ACM.
12. Beat Weiss, Hong Linh Truong, Wolfgang Schott, Thomas Scherer, Clemens Lombriser, and Pierre Chevillat. Wireless sensor network for continuously monitoring temperatures in data centers. *IBM RZ 3807*, 2011.
13. H. Viswanathan, Eun Kyung Lee, and D. Pompili. Self-organizing sensing infrastructure for autonomic management of green datacenters. *Network, IEEE*, 25(4):34 –40, july-august 2011.
14. R. R. Schmidt, E. E. Cruz, and M. Iyengar. Challenges of data center thermal management. *IBM Journal of Research and Development*, 49(4.5):709 –723, july 2005.
15. J. Fredrik Karlsson and Bahram Moshfegh. Investigation of indoor climate and power usage in a data center. *Energy and Buildings*, 37(10):1075 – 1083, 2005.
16. A Rowe, M E Berge, and R Rajkumar. Sensor andrew : Large-scale campus-wide sensing and actuation. *International Business*, 55(1):1–14, 2011.
17. Dave Locke. Mq telemetry transport (mqtt) v3.1 protocol specification, 2010.
18. A. J. Stanford-Clark and G. R. Wightwick. The application of publish/subscribe messaging to environmental, monitoring, and control systems. *IBM J. Res. Dev.*, 54(4):396–402, July 2010.
19. Stephen Wilson and Jeremy Frey. The smartlab: Experimental and environmental control and monitoring of the chemistry laboratory. In *Proceedings of the 2009 International Symposium on Collaborative Technologies and Systems*, CTS '09, pages 85–90, Washington, DC, USA, 2009. IEEE Computer Society.
20. Veselin Ganev, Dave Chodos, Ioanis Nikolaidis, and Eleni Stroulia. The smart condo: integrating sensor networks and virtual worlds. In *Proceedings of the 2nd Workshop on Software Engineering for Sensor Network Applications*, SESENA '11, pages 49–54, New York, NY, USA, 2011. ACM.
21. Karl Aberer, Manfred Hauswirth, and Ali Salehi. A middleware for fast and flexible sensor network deployment. In *Proceedings of the 32nd international conference on Very large data bases*, VLDB '06, pages 1199–1202. VLDB Endowment, 2006.
22. "About us - Pachube.", 2007. `http://community.pachube.com/about`.
23. Modbus over serial line - specification & implementation guide - v1.0, February 2002. `http://www.modbus.org/docs/Modbus_over_serial_line_V1.pdf`.
24. Xmpp standards foundation. `http://xmpp.org`.
25. "Metageek's WiSpy". `http://www.metageek.net/products/wi-spy/`.
26. "Memsic's TelosB". `http://www.memsic.com/products/wireless-sensor-networks/wireless-modules.htm`.