A Sensing Platform for High Visibility of the Datacenter

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Abstract. Data centers are large energy consumers and a substantial portion of this power consumption is due to the control of physical parameters, which bring the need of high efficiency environmental control systems. In this paper, we describe a hardware sensing platform specifically tailored to collect physical parameters (temperature, pressure, humidity and power consumption) in large data centers. This platform is an important enabler to find opportunities to optimize energy consumption. We also introduce an analysis of the delay to obtain the sensing data from the sensor network. This analysis provides an insight into the time scales supported by our platform, and also allows to study the delay for different datacenter topologies.

1 Introduction

Data center's large power consumption justifies a special attention to the design of energy efficient data centers. Power usage effectiveness (PUE) has become the metric to measure data center efficiency. It measures how much of the total energy consumed is really spent on IT work other than on facility's overhead, like lightning, cooling and power distribution, and it is given by: PUE = (IT Equipment Energy + Facility Overhead) / Energy IT Equipment Energy. It is desirable to measure it with a high spatio-temporal granularity, so that the PUE metric is as accurate as possible and to enable better understanding of the power consumption in the datacenter. This better understanding may lead to great reductions through e.g. better load balancing, power distribution, or reduced air conditioning usage [1].

To have a full picture of the datacenter environment, it is important to collect air pressure, temperature, humidity and power consumption data at a high granularity (in time and space). The relevance of collecting these parameters is discussed in the next paragraphs.

In a typical datacenter, IT equipment is organized into rows, with a cold aisle in front, where cold air enters the equipment racks, and a hot aisle in back, where hot air is exhausted. Computer-room air conditioners (CRACs) are commissioned to cycle the air, by pushing the cold air and returning the hot air

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to be cooled again. The CRAC systems are responsible for a big share of the facility overhead energy, and in order to achieve a more uniform thermal profile, special effort must be given on airflow distribution, by preventing cold and hot air from mixing and by eliminating any hotspots. Better understanding of the airflow can be addressed by placing pressure and temperature sensors.

By measuring the local pressure, it is possible to estimate the speed and direction of the airflow between the sensed points and possibly identify unwanted mixtures or flow bottlenecks, as shown in [2]. It can also be used for workload-balancing among servers like in [3] where the patent application describes a system that uses a load balancer to shift tasks among servers based on their particular cooling needs, which are related to air pressure drop across the server.

With fine grained temperature measurement it becomes easy to localize hotspots, and by crossing such information with pressure information, better details of the airflow can be estimated, thus lead to better tuned CRAC systems.

Another important environmental parameter is the local humidity. Higher relative humidity decreases the chances of static electrical discharges that can damage the IT equipment and, at the same time, increases the heat transfer from the server to the cooling airflow. But too much water particles in the air reduces the lifetime of the IT equipment and increases the chance of water condensation, which is not desirable. Several entities, such as the American Society of Heating, Refrigerating & Air-Conditioning Engineers (ASHRAE), provide guidelines with allowed and recommended values of relative humidity, as well as for dry bulb temperature, maximum dew point, maximum elevation and maximum rate of temperature changes, as seen in [4].

We present in this paper a sensing platform for collection of temperature, pressure, humidity and local (rack-level) power consumption. The development of the platform was centered on the specific application scenario of energy optimization in large datacenters, focusing on high resolution sensing: several sensing points per rack, sampled at sub-seconds time intervals. Evidently, for such system to be practical, cost is an important factor to consider. We detail the design of this platform and develop an analysis of the time to obtain the sensing data from the sensor network. This analysis also allows to see the tradeoff between the number of sensing points per datacenter row and the speed of data collection.

2 Related Work

Green data centers have received considerable attention in recent research literature. Some recent approaches rely on building software models through a joint coordination of cooling and load management [5, 6], or by formulating an energy minimization problem, subject to service delay and Quality of Service (QoS) constraints. In this class it is worth to mention dynamic voltage scaling [7, 8] and on/off power management schemes [9] – [11]. 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 [12]. For example, in [5], authors stress that their model has several parameters that need to be determined for specific applications.

Given such models, acquiring real-time data at a fine enough spatio-temporal resolution becomes an important topic, as this data can be used to validate models and keep their inputs updated at run-time. Nevertheless, this problem poses new challenges and research issues concerning the type, number and placement of sensors [12].

Some works [13, 14] 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. We differ from such approaches in the sense that we want very fine-grained (in space and time) gathering of power and environmental parameters, including physical quantities other than temperature. Using a mixed wire/wireless solution, [13] obtained a average one-round collection time of approximately 6 seconds for 50 nodes. They also deployed 694 sensor nodes in a data-center, reading every cluster of 4 at most at every 30 seconds. In this work ([13]), for every cluster there was a wireless station and nodes where powered via USB, which makes the system dependent on having a powered USB port available (this might be a problem, since the server to where the node is connected to cannot be powered off, for example). A pure wireless solution was presented in [14], where it was reported a deployment of 107 battery powered wireless nodes, taking 3 seconds to sample all of them (not considering data losses). The experiment only lasted for 35 days before the battery had to be replaced, which is not practical for large, long-lived deployments.

Our proposed system is based on a hierarchical, modular, flexible and fine-grained sensor network architecture, where data is collected from heterogeneous sensors (including power), placed in each rack. The analysis of their inter-correlations will enable closer examination and a better understanding of the flow and temperature dynamics within each data center [15]. To our knowledge, no previous work enables correlating power and environment characteristics on a per rack or per-server granularity with such temporal resolution.

3 Overview

The proposed sensor network architecture is a combination of wired and wireless technologies, designed to achieve high spatio-temporal resolution of data center rooms, keeping system's flexibility and modularity, with a low latency and low cost.

Our system is designed to cover the datacenter first by a short range bus that covers the communication needs inside each rack, a longer range bus that covers each row in the datacenter and then wireless communication is used to gather the data from the entire datacenter room. Four different types of devices cover each of these levels (rack, row and room): (i) *Sensing Units* sense the physical parameters (temperature, pressure, humidity, and power) in each rack, then (ii) *Sensor Nodes* collect the sensing data for the entire rack, and (iii) Wireless Base Stations (*WBS*s), collect data from several Sensor Nodes in a

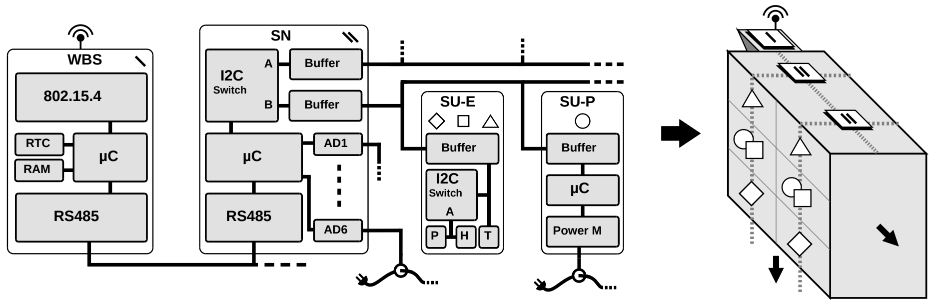


Fig. 1. Network Architecture and Layout

row, as represented in Figure 1. Finally, (iv) *Gateways* collect data from all of the *WBS*s in a datacenter room.

Starting at the lower level, our sensor network consists of two different types of Sensing Units: (a) a small passive sensing unit for measuring environmental quantities, with at most one temperature, one humidity and one pressure digital sensor, and (b) a power metering unit with real, active, and reactive power measurement capabilities, as presented in Figure 1 by *SU-E* and *SU-P* respectively. The environmental Sensing Units can be manufactured according to the sensing and cost needs, by having any combination of sensors on it, what is represented by the three different shapes. Both sensing units deliver data to the next level in the hierarchy, through a wired short range bus (I2C), projected to cover only one rack of servers (back and front).

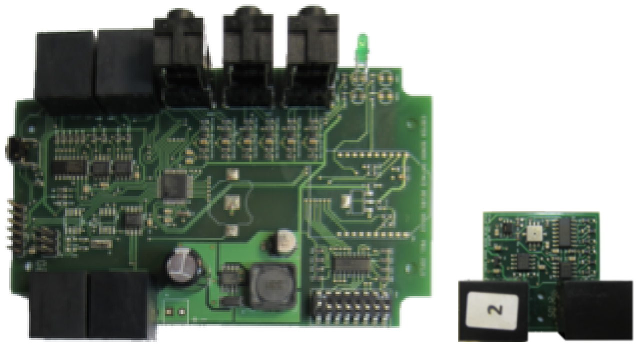
At the next level, the Sensor Node is responsible to collect the data of all the Sensing Units attached to it and possibly to perform simple data aggregation and sensor fusion before delivering it to the next level in the hierarchy using a longer range wired bus (MODBUS).

WBSs are responsible for querying the Sensor Nodes within their respective cluster, and again perform data aggregation, sensor fusion and data analysis. They communicate then with devices at the next level in the hierarchy to deliver the relevant data. Gateways then provide the data gathered from the sensor network to the data distribution system in a standard format. From this point on, sensing data is published at a publish/subscribe middleware that distributes the acquired data to different applications, where each of them will use such information with different proposes (alarms, data logging, visualization, etc).

Each Sensor Node can be connected up to 52 temperature sensors, 54 power meters, 14 pressure sensors and 14 humidity sensors. The following section describes in more detail each of the system components.

4 Platform Details

Well-known protocols, network architectures and of-the-shelf electronic components had to be chosen to compose the system, considering that the final objec-



(a) Sensor Node (b) Sensing Unit

Fig. 2. Hardware Platforms

tive was to build a fully functional, industry ready, sensor network with very low cost. Besides the architecture, the technology chosen to implement the network is described below.

4.1 Sensing Unit

With the popularization of two-wire I2C buses on motherboards, cellphones and on general embedded systems, many companies are nowadays developing sensors with digital I2C output, by embedding the micro-mechanical sensor, signal amplifiers, analogue to digital converters, memory and a I2C front end to manage with the communication on the bus. These Systems-on-Chip enable high accuracy and reliability measurements, since this decreases the probability of data corruption due to any external interference. It also prevents calibration issues found on pure-analogue sensors measurements, since digital sensors are factory calibrated and digitally compensated. Due to these reasons, I2C sensors were used to connect the several sensing units.

Some limitations of I2C buses had to be overcome to make its usage practical in this application. First, buffers had to be added as an interface between the I2C bus lines and every circuit board attached to it, in order to allow the I2C to operate over longer distances, by increasing the robustness of the logic signals of the standard I2C buses. Second, switches had to be added to every Sensing Unit on the bus in order to allow the usage of more than one sensor with non-configurable addresses, making it accessible from the main bus.

Figure 2(b) depicts one Sensing Units with temperature, humidity and pressure sensors. The temperature sensor used is a low cost and low power device with 1.5°C accuracy, maximum resolution of 0.0625°C and minimum and maximum conversion times between 27.5 and 300ms. The humidity sensor has 1.8%RH accuracy, with maximum 0.04%RH resolution and minimum and maximum conversion times between 3 and 29ms, both the temperature and humidity sensors suitable for the application, where the focus are in changes in major scales according to the ASHARE guidelines [4], which specifies a range of dew points between 5.5°C (for 60%RH) and 15°C. The pressure sensor ranges from 300 to 1100hPa, with an accuracy of +-1hPa typical and 0.03hPa of resolution with minimum and maximum conversion times between 3 and 25.5ms, also suitable for the application, where typical pressure variation values inside datacenter's are in greater orders of magnitude, as seen in [2].

The Power Meter Sensing Unit is composed by a dedicated chip which interfaces with the power line, and provide real, reactive, and apparent power measurements to the embedded computational unit, which is responsible for interfacing with the I2C bus as a slave, and to deliver such information to the master, at the next level.

To both Sensing Units, the power is carried into the same cable as the I2C data, and locally converted from 5 to 3.3V by a low-drop LDO converter, for more stable and lower ripple power supply for the sensors, which are sensitive to such variations.

4.2 Sensor Nodes

A Sensor Node is a communication/computation enabled device, physically linked over the I2C bus (also trough buffers) to a number of Sensing Units.The Sensor Nodes gather the data from the Sensing Units and, in turn, answer to data requests from the WBS. Figure 2(a) depicts a Sensor Node.

To keep cost and complexity low at this tier of the network architecture, the Sensor Nodes communicate with one Wireless Base Station (WBS) over a bus, e.g., using a RS485/MODBUS technology [16]. In particular, the WBS node acts as a local coordinator and master of the bus.

The Sensor Node is also composed by: (i) six analogue inputs suited for current measurement, connected to external current transducers attached to the power lines, as a cheap and simple alternative for basic current measurement; (ii) two I2C buffered ports through one switch, responsible for duplicating the bus capacity in terms of addressable devices, and enabling a better mechanical placement for cables to go to the back and front of a rack, and (iii) one RS485 port for the MODBUS.

The power supply for the Sensor Nodes is carried by a twisted pair cable, along with the MODBUS data, in another pair. At every Sensor Node, a high efficiency DC-DC step down converter, converts from 48 to 5V for the local supply. This is an important feature as it reduces the number of cables that connect to each node, facilitating installation of the devices.

4.3 Wireless Base Stations (WBSs)

The WBS is directly connected to a power source and supplies power through a twisted pair cable to all the Sensor Nodes in that bus. In all the nodes on this bus, the voltage is locally converted to lower values by a step-down switched power supply for a higher system efficiency. Wires running in the same cable form a serial data bus (MODBUS over a RS485 connection) that interconnects the Sensor Nodes.

The WBS is based on the same printed circuit board as the Sensor Node, missing the sensors interfaces, and with some extra components, like one external non-volatile ferrite random access memory (FRAM), used as a buffer and for diagnosing the system in cases of failures or power cuts (by keeping the last operational state). The WBS also includes a real-time clock used for time stamping the data packets.

The WBSs act as IEEE 802.15.4 cluster heads and are connected with each other in a mesh topology. A common Gateway is in charge of gathering measurements and sending them over long range communication technology (e.g., WiFi, Ethernet). In terms of HW platforms, the WBS node will be the same platform as a generic Sensor Node, with an on-board ZigBee radio. Thus, each Sensor Node can become a WBS with minimal modifications, i.e., just by plugging the wireless module and uploading a different firmware.

4.4 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.

5 Delay Analysis

In this section we will develop an analysis of the time to transmit sensor data using our system. The purpose of this analysis is to show that our system can exhibit very low delays in the presence of a large number of sensing points.

This analysis will also enable us to study the communication delay as we add Sensor Nodes to the network. We consider that each Sensor Node added has N_{su-sn} Sensing Units attached to it, where each Sensing unit has three 16 bit sensors. For every N_{sn-wbs} Sensor Nodes added to the network, one WBS has to be added also. The total number of Sensor Nodes is defined as N_{sn}.

These parameters (N_{su-sn} and N_{sn-wbs}) are defined according to the topology of the data center room. Therefore, our analysis can allow evaluating the tradeoff between the delay and the network organization.

5.1 Calculating the Response Time

The response time R required to collect data from all the sensors is given by adding together the time to transmit all the wireless requests to all WBS (t_{req}) and also the corresponding replies (t_{rep}), as given by Equation (1).

$$R = (t_{req} + t_{rep}) \tag{1}$$

The time to transmit all requests is computed by the sum of the time required to transmit a request to each WBS (there are $\lceil \frac{N_{sn}}{N_{sn-wbs}} \rceil$ WBS:s in the network) with the worst-case blocking time, B_{mb}, is given by Equation (2).

$$t_{req} = \left\lceil \frac{N_{sn}}{N_{sn-wbs}} \right\rceil \times (t_{wtx}(S_{wreq}) + B_{mb}) \tag{2}$$

where the $t_{wtx}(S_{wreq})$ is the time to transmit a request packet in the wireless 802.15.4 network including all protocol overhead for a packet with S_{wreq} bits of payload, and will be defined later. B_{mb} is a constant given by the longest data transaction over the MODBUS, which corresponds to the largest task to be executed by the WBS in a non pre-emptive system.

The time to transmit all replies is given by Equation (3) as follows:

$$t_{rep} = \left(\left\lfloor (N_{su-sn} \times N_{sn}) \times \frac{S_{sd}}{S_{mwp}} \right\rfloor + 1 \right) \times t_{wtx}(S_{mwp}) \tag{3}$$

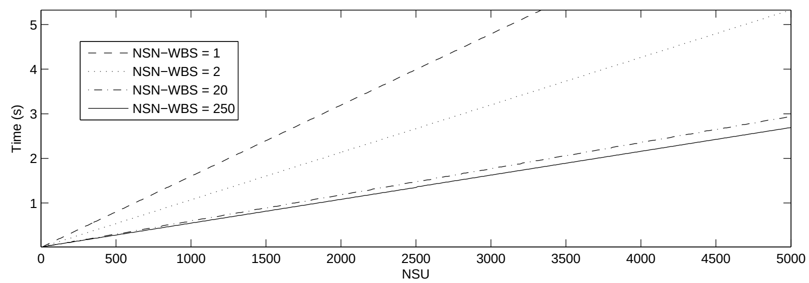
where S_{sd} is the size of the sensor data to be transmitted by each Sensor Unit and S_{mwp} is maximum wireless data payload, after accounting for all protocols headers. $t_{wtx}(S_{mwp})$ is the time to transmit a packet in the wireless IEEE 802.15.4 network with the maximum possible payload (mwp bits) and will be defined in Section 5.2.

5.2 Calculating the Wireless Transmission time

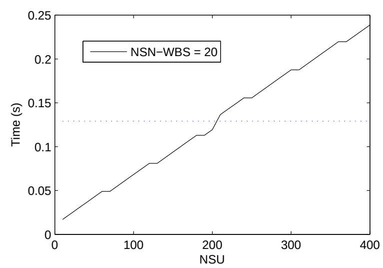
The reasoning applied to calculating the wireless transmission time ($t_{wtx}(S)$) is similar to the one found in [17, 18] when analyzing the maximum theoretical throughput of a non-beacon enabled IEEE 802.15.4. The time to send a IEEE 802.15.4 packet with payload size of S bits if given by:

$$t_{wtx}(S) = T_{ib} + t_{ppdu}(S) + T_{ack} + T_{ifs} \tag{4}$$

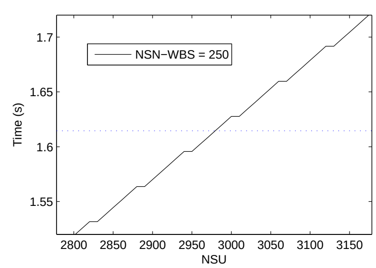
where T_{ib} is the initial backoff period, which depends on the parameter $macMinBE$, and, by default, $macMinBE = 3$, resulting in $T_{ib} = 1120\ \mu s$). The time to transmit the PHY protocol data unit (ppdu) with a payload size of S bits is denoted by $t_{ppdu}(S)$. The time to transmit an acknowledgment is defined as $T_{ack} = T_{ackppdu} + T_{rxtx} = 544\ \mu s$ since it must include the time to send the acknowledgment packet ($T_{ackppdu} = 352\ \mu s$ as defined in the standard [19]) and the time for the transceiver to switch from receive to transmit ($T_{rxtx} = 192\ \mu s$ is the maximum value defined in [19], and this is the value found in the 802.15.4 transceivers employed [20]). The interframe spacing (IFS), T_{ifs}, is set to the value of the long IFS defined by the standard, 640 μs (actually, this is only used when the size of the MAC protocol data unit (MPDU) to be sent is above or equal to 18 bytes [19]).



(a) R (Eq. 1) for $N_{su-sn} = 10$, with varying N_{sn-wbs}



(b) $N_{sn-wbs} = 20$



(c) $N_{sn-wbs} = 250$

Fig. 3. Network Response Time

The time to transmit the ppdu with a payload of size S bits, can be defined as:

$$T_{ppdu}(S) = (S_{hdr} + S_{zbee} + S + S_{ftr}) \times \tau_{bit} \tag{5}$$

where S_{hdr} is the sum of the sizes of the synchronization header (SHR), PHY header (PHR) and MAC header (MHR; from [19]: $S_{SHR} = 40$; $S_{PHR} = 8$; $S_{MHR} = 56$ bits). The size of the ZigBEE protocol headers is $S_{zbee} = 41 * 8$ bits, and the size of the MAC footer is $S_{ftr} = 16$ bits. The time to transmit one bit is $\tau_{bit} = 4\ \mu s$ (for a data rate of 250 kbps).

5.3 Delay Results

Instantiating the response time given by Equation (1) for $N_{su-sn} = 10$ and $N_{sn-wbs} = \{1, 2, 20, 250\}$ results in Figure 3(a). We have selected these values for N_{sn-wbs} because they exemplify well the trend as we change this parameter. For these calculations, we have used $S_{wreq} = 16$ bits (a request with a two-byte identifier) and $S_{mwp} = 576$ bits (the maximum IEEE 802.15.4 payload minus the overhead defined in Equation (5)).

Not surprisingly, in Figure 3(a), we can see that R is reduced as we have more Sensor Nodes attached to each WBS, but this reduction is increasingly smaller. We can see that our system can support a large number of sensor points and still enable very fast, automatic response to events detected by the sensor system.

Figures 3(b) and 3(c) present another aspect related to the network topology, which must be considered when designing the network. The horizontal line in both plots shows the time to gather the data from all Sensor Nodes attached to the WSB (20 Sensor Nodes in Figure 3(b), and 250 in Figure 3(c)). The way the network is designed, if one implements a network with N_{sn} below the intersection between the horizontal line and the response time, the wireless communication cycle of the WBS will be faster than the communication cycle on the MODBUS. Thus, the WBS would repeatedly transmit data from previous communication cycles. N_{sn-wbs} should be set such that the lines intersect at the desired N_{sn}. Something that can be easily found, given the analysis presented in this section.

In Figures 3(b) and 3(c), we can see a stepped behavior of the response time, with the growth of the N_{su}. One step happens at each $6 \times N_{su-sn}$. The reason for this step is that, as we add Sensor Nodes, there is the need for and extra packet to be sent (the length of the packet and number of packets needed depends on N_{su-sn} and also on the maximum payload mwp). In this scenario, the sensor data for the 7th Sensor Nodes fits in the same number of packets, and thus the delay does not increase. A bigger step is given at every N_{sn-wbs}, due to the overhead of adding one WBS more.

6 Conclusions

We have presented a platform for acquiring the physical parameters of a datacenter. This platform was developed as a mix of wired and wireless communicating nodes, such that it can enable flexible monitoring of the datacenter at a very high temporal and spatial resolution of the sensor measurements, while keeping the cost per sensing point very low. Compared to previous work, we enable much higher sensing resolution (several sensing points per rack, sampled at subsecond frequency), maintaining cost low and ease of installation. Acquiring such physical parameters at a very high resolution is important to find opportunities to optimize energy consumption, minimize local hot-spots, achieve more accurate predictive maintenance, perform more accurate billing, and it also enables very fast response to changes in the measured parameters, including automated actuation.

We also presented an analysis of the delay of our system. This analysis enabled us to study the communication delay as we add Sensor Nodes to the network, and has shown that our system can exhibit very low delays in the presence of a large number of sensing points. This analysis also allows to try different network deployments and check the tradeoff between different topologies (described by parameters N_{su-sn} and N_{sn-wbs}) and the resulting delay.

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