Final Technical Report

Project Title: Recovery Act: A Measurement – Management Technology for Improving Energy Efficiency in Data Centers and Telecommunication Facilities

Award Number: DE-EE0002897

Project Period: 01/31/2010 – 03/31/2012

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Date of Report: 06/28/2012

Acknowledgement: This report is based upon work supported by the US Department of Energy under Award No DE-EE0002897

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List of Acronyms

Å	Angstrom
AC	Alternating Current
ACU	Air Conditioning Unit
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CCB	Collection Computer Board
CDU	Cooling Distribution Unit
CFD	Computational Fluid Dynamics
CRAC	Computer Room Air Conditioning
DC	Data Center
DCIE	Data Center Infrastructure Efficiency
IT	Information Technology
LBNL	Lawrence Berkley National Laboratory
MMT	Measurement and Management Technology
PDE	Partial Differential Equation
PCB	Printed Circuit Board
SPB	Signal Processing Board
TF	Telecom Facility
VHO	Video Hub Office

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Summary

Data center (DC) electricity use is increasing at an annual rate of over 20% and presents a concern for the Information Technology (IT) industry, governments, and the society [1,2]. A large fraction of the energy use is consumed by the compressor cooling to maintain the recommended operating conditions for IT equipment [1]. The most common way to improve the DC efficiency is achieved by optimally provisioning the cooling power to match the global heat dissipation in the DC. However, at a more granular level, the large range of heat densities of today's IT equipment makes the task of provisioning cooling power optimized to the level of individual computer room air conditioning (CRAC) units much more challenging. Distributed sensing within a DC enables the development of new strategies to improve energy efficiency, such as hot spot elimination through targeted cooling, matching power consumption at rack level with workload schedule, and minimizing power losses. The scope of Measurement and Management Technologies (MMT) is to develop a software tool and the underlying sensing technology to provide critical decision support and control for DC and telecommunication facilities (TF) operations.

A key aspect of MMT technology is integration of modeling tools to understand how changes in one operational parameter affect the overall DC response. It is demonstrated that reduced order models for DC can generate, in less than 2 seconds computational time, a three dimensional thermal model in a 50 kft² DC. This rapid modeling enables real time visualization of the DC conditions and enables "what if" scenarios simulations to characterize response to "disturbances". One such example is thermal zone modeling that matches the cooling power to the heat generated at a local level by identifying DC zones cooled by a specific CRAC. Turning off a CRAC unit can be simulated to understand how the other CRAC utilization changes and how server temperature responds.

Several new sensing technologies were added to the existing MMT platform: (1) air contamination (corrosion) sensors, (2) power monitoring, and (3) a wireless environmental sensing network. All three technologies are built on cost effective sensing solutions that increase the density of sensing points and enable high resolution mapping of DCs. The wireless sensing solution enables Air Conditioning Unit (ACU) control while the corrosion sensor enables air side economization and can quantify the risk of IT equipment failure due to air contamination.

Validation data for six test sites demonstrate that leveraging MMT energy efficiency solutions combined with industry best practices results in an average of 20% reduction in cooling energy, without major infrastructure upgrades. As an illustration of the unique MMT capabilities, a data center infrastructure efficiency (DCIE) of 87 % (industry best operation) was achieved.

The technology is commercialized through IBM System and Technology Lab Services that offers MMT as a solution to improve DC energy efficiency. Estimation indicates that deploying MMT in existing DCs can result in an 8 billion kWh savings and projection indicates that constant adoption of MMT can result in obtainable savings of 44 billion kWh in 2035. Negotiations are under way with business partners to commercialize/license the ACU control technology and the new sensor solutions (corrosion and power sensing) to enable third party vendors and developers to leverage the energy efficiency solutions.

Introduction

In many of today's DCs the energy used for cooling can be over 20% of the total energy use [1-4]. With increasing energy prices and also a commitment from many industrial and government organization to reduce the carbon footprint, there is a need to develop comprehensive technologies for energy efficiency. There are many commercial environmental solutions to measure or to model the temperature, relative humidity, and air flow in DCs but those solutions tend to be fragmented and require sophisticated integration tools. There is a clear need for a common platform that would integrate both the software tools and the underlying technology components (sensing and control) to provide critical decision support and controls for DC/TF operations.

The key component of such technologies is scalability at existing or new facilities under a common platform for data management, modeling, and visualization. To model DC operation external data sources like IT server sensors, building management system, and complementary data like weather should be integrated. For DCs that use outside air for cooling, it may be necessary to understand how indoor air quality is affected by the location of pollution sources and how pollution spreads based on wind speed and direction.

While monitoring the DC/TFs is a prerequisite for energy efficiency, control strategies are required to optimize the operation of air conditioning units (ACU) as well as of the free cooling (water and/or air side). For optimum control, the environmental sensors would provide feedback data to support the control settings and to validate the attainable efficiency.

Air side economization is investigated as the most direct way to reduce the energy used for cooling. Based on simulations of DCs operations, Lawrence Berkley National Laboratory (LBNL) demonstrated that outside air cooling can reduce up to 25% of the total energy used for cooling [5]. However, with outside air cooling, the relative humidity may go as high as 90% and can create a potential risk of condensation [5]. Another concern for using outside air is the possibility to introduce air pollutants along with the "fresh air". Air pollution can result in an increased particulate matter (dust) and corrosion of IT in the DC [6]. Studies undertaken by LBNL demonstrated that corrosion rate of the outside air can exceed 300 Å/month [7], a value that is considered the upper level of air pollution for reliable IT operations [8]. Industry standards recommend a corrosion rate of 300 Å/month for copper and 200 Å/month for silver to be maintained in a DC [6,8]. Thus, cost effective corrosion sensors could enable the use of outside air while protecting the IT equipment.

The effectiveness of recommendation from energy efficiency solutions can be achieved through measurement of a common metric before and after energy optimization. One such metrics is the data center infrastructure efficiency (DCIE) that is calculated by dividing IT equipment power by total facility power. To improve the DCIE for a DC, besides environmental sensing, additional actions should be considered like capacity planning, virtualization, consolidation, provisioning and cloud computing approaches.

In this report the energy savings obtained in field testing the MMT technology at 6 test sites is described and the obtainable energy savings using MMT are quantified. Detailed description of achievable savings in a DC is included for a test site where a DCIE of 87 % was demonstrated. Descriptions of the sensor technology and validation studies are presented along with the description of the modeling tools.

Background

The energy efficiency of DC is largely determined by the extent to which “best practices” are implemented, both when physically planning and operating the DC [3,9] For example, power consumption of the cooling system, which is a significant fraction of the total power needs, is dominantly governed by the placement of the IT or switching equipment, the chilled air flow control mechanisms, perforated tile placement, confinements of the cold and warm aisles, among other factors.

Many of the DC “best practices” are well documented in the open literature [3,9] and in addition, there are several solutions such as energy assessments, virtualization and consolidation technologies, and modeling services which are all designed to improve DC energy efficiency.

Every DC is different and to improve energy efficiency for a particular DC, a subset of best practices may apply. To develop a solution that can be applied across many data centers, a set of requirements has to be integrated:

- 1) Scalability: the technology can be applied to any type of data centers on large scale for cost effectiveness
- 2) Provability: the technology should be able to measure quantitatively the resulting efficiency improvements based on an industry acceptable standard metrics
- 3) Manageability: physical energy efficiency improvements have to be manageable *without* compromising reliability of the operation. Computational Fluid Dynamics of “*what-if*” modeling scenarios ensures that any implemented changes will not compromise the reliability.
- 4) Integrate-ability: significant energy efficiency improvements will originate from integrating the various dimensions involved in DC/TFs through a single management platform
- 5) Feasibility: tighter integration between IT and facilities will allow targeting virtualization and consolidation projects to provide maximum benefits without major infrastructure investments.

To address these challenges, MMT 2.0 was developed under supports from the Industrial Technologies Program of the DOE Office for Energy Efficiency and Renewable Energy (EERE) to improve energy efficiency in the information technology sector. MMT 2.0 is being built upon an earlier developed solution, which is complemented with a real-time, high resolution measurement system using sensor networks (for temperature, power, humidity, corrosion rates etc.), embedded IT equipment sensors and other data sources (e.g., from building management systems). The technology deploys novel measurement-based, energy and thermal modeling methods for generating real-time data (i.e. 3D heat, power distributions, cooling provisioning, corrosion risks for outside air usage etc.) for optimum manageability of the facilities’ energy efficiency. MMT 2.0 will provide control of the fans and set points in the air conditioning units (ACU) as well as manage free cooling (water and/or air side). The technology will yield ongoing best practices recommendations including the physical IT layout and leverage circuit-level power monitoring, which enables not only optimum provisioning but also reduces power delivery losses.

Results

The MMT technology was field tested at 6 locations chosen to be representative of operating DCs and TFs; three IBM's facilities in Boulder (CO), Raleigh (NC), and Poughkeepsie (NY) in addition to three AT&T facilities in Anaheim (CA), Bothell (WA), and Dallas (TX).

As an initial step, the MMT mobile cart was used to map the temperature and the relative humidity in DC/TFs to establish baseline and generate recommendations. In the second phase MMT was deployed to monitor spatio-temporal changes and to assess how recommendations improved the DC efficiency.

Savings were demonstrated for each of the 6 test sites as a result of the deployment of MMT. The average savings for the sites was 24.8% of the cooling load and 6.3% of the IT load (Table 1).

					Annual energy Savings	Annual savings
Site	UPS Load kW	Required # CRAC	Active # CRAC	# CRAC shutdown	MWh/yr	\$/yr
Test site #1	5458	117	157	22	1830	\$91,516
Test site #2	3344	57	129	66	3798	\$341,814
Test site #3	1855	39	55	5	325	\$15,595

Table 1 Energy savings achieved at 3 field test sites based on MMT analysis and recommendations.

A wireless sensing network was developed for flexible deployments in TFs where equipment layout is frequently changing. The wireless sensing network is based on low power radios that allow a battery lifetime of 7 years in the field with a sampling rate of 1 minute. The wireless sensing solution reduces the cost of single point sensing by eliminating the wire and power requirements that are associated with wired solution. Temperature, relative humidity, air flow, pressure and corrosion sensing are integrated into the wireless sensing solution. The technology was tested at AT&T's Anaheim test facility for over 1 year period (Fig 1).

A control firmware and algorithm for the wireless sensor network was developed to control Air Conditioning Units (ACUs). The control scheme optimizes the utilization of the ACU units by turning off systems that are running at very low utilization (<20%) while shifting the load to ACUs that have medium utilization (~50%). In a typical DC, the control can shut off around 20% of the ACUs, resulting in energy savings up to 10%. Multiple layers of security and control loops were implemented to minimize risk and to prevent situations where overheating may occur. The DC is continuously monitored by temperature and pressure sensors to maintain recommended operating temperature and cooling capacity.

Fig 1 Wireless sensing layout at a telecom facility with temperature sensing string attached to the rack and the radio position on the top of rack.

A detailed performance auditing of the IBM's Green Data Center in Poughkeepsie revealed many inefficiencies and that the DC has a DCIE of 74 %. Some of the recommendations generated by MMT were the elimination of energy “leaks”, improving air flow through perforated tiles placement, and workload consolidation on servers. Furthermore based on “what-if” simulations, the DC layout was rearranged such that more equipment could be deployed in the DC without increasing the required cooling power. The implementation led to a DCIE metrics of 87 % representing one of the highest levels of efficiency in the industry. MMT was instrumental in implementing the energy efficiency measures and is continued to be used as an active tool to monitor in real time the DCIE metrics for the Poughkeepsie data center (see Appendix A for more details).

1. MMT Technology Development

1.1 Corrosion sensors

Outside air cooling is the most economical way to reduce energy consumption in DCs, TFs and industrial facilities. Many DC operators are concerned about the accidental introduction of air pollutants in the DCs along with the fresh air. This may be the case if the DC is located in metropolitan or industrial areas, in locations where wild fires, occur or geographies where large amount of fertilizer/chemicals are used in a nearby location. Continuous air filtering is a possible solution to minimize contamination but would increase the operating cost. The most effective way to prevent accidental pollution of the DC is to monitor in real time the air contamination.

A common way to monitor the air contamination is the use of corrosion sensors that measure the reactivity of the contamination molecules with metal films. The corrosion sensor can be an integral part of a contamination management solution to monitor the air quality and control the intake valve positions that allow mixing of outdoor/indoor air ratio. By controlling the amount of outside air used for cooling along with temperature and relative humidity, the corrosion rates can be maintained at acceptable values at period of times when outdoor pollution may be higher.

For corrosion sensor development, large scale semiconductor fabrication processes were leveraged through wafer scale deposition of the metal traces on silicon

substrates. For corrosion rate measurement, the resistance of the metal traces is electrically measured as the film thickness is reduced as pollutant molecules interact with the metal film surface. The technology was developed for silver and copper and the metal film thickness was chosen to be 1.5 μm (lifetime of 7 years at a corrosion rate of 300 $\text{\AA}/\text{month}$) and the detection has a sensitivity of 1 $\text{\AA}$ change in film thickness.

The corrosion sensor was designed to be easily replaceable in the field once the sensor film is consumed. The sensor is attached to a replaceable Printed Circuit Board (PCB) card that fits into the communication board and the PCB card is replaced once the sensor element is consumed (Fig 2). The corrosion sensor performance was compared with commercially solutions, with the resistive technique fairing better than the quartz crystal or metal coupon measurements.

Fig 2 Silver corrosion sensor with sensor element and the detection electronics. Sensor lifetime is 7 years in an environment with a corrosion rate of 300 $\text{\AA}/\text{month}$.

The sensitivity of the corrosion sensor to gaseous pollution was assessed in a data center where the indoor corrosion rate was compared with the outdoor fluctuation of NO_2 , and SO_2 concentration (Fig 3). When the outdoor contamination is low (from 10 am until 4 pm), the corrosion rate drops below 300 $\text{\AA}/\text{month}$ while in general the corrosion rate can be as high as 600 $\text{\AA}/\text{month}$ the rest of the days. The indoor corrosion rate was tracking the outdoor pollutants concentration, demonstrating the link between high corrosion rate and poor air quality. The data demonstrate that outdoor pollution levels are driving the indoor corrosion rate and there is a direct correlation between outside air pollution and indoor corrosion rate (that is expected if the DC is not fully sealed from the outside).

Corrosion is a synergistic result of temperature, humidity, air flow and gaseous contamination. To identify the main driving factors for corrosion, a facility wide temperature, relative humidity, and air flow should be monitored and modeled to identify high corrosion risk zones. Field test of the corrosion sensor technology demonstrated that the corrosion rate measured in a DC is dependent on the location where the sensor is placed. To achieve the best repeatability, the corrosion sensors can be placed at the outlet of ACU units (under the raised floor) or at the rack air intake. The corrosion sensors were tested at a TF Anaheim where a the corrosion rate of less than 120 $\text{\AA}/\text{month}$ was measured during the summer months and the value increased closer to 200 $\text{\AA}/\text{month}$ during autumn and winter months.

Fig 3 Indoor corrosion rate and the corresponding outdoor SO₂ and NO₂ gaseous concentration for a two day period.

The corrosion rate in an air side economized data center depends on the amount of outside allowed in the DC. In one of the test studies, the corrosion rate was below 120 Å/month during summer when no air side economization was used. During the winter season, the air side economizer was enabled and occasionally the corrosion rate increase for short periods of time well above 300 Å/month while most of the time the corrosion rate was below 200 Å/month (Fig 4).

Fig 4 Corrosion rate in an air side economized data center.

The corrosion data from the economized data center proves that contamination monitoring would be beneficial as the corrosion rate can have excursion to large values. The corrosion sensing solution is fully integrated with MMT and is an effective solution to preserve the reliability of IT equipment in air side economized DCs or for DCs situated in polluted geographies.

A corrosion management solution was developed to manage the risk in data center due to air pollution or operation of DC at high level of temperature and humidity. Since corrosion can be accelerated by increased temperature and relative humidity levels, optimizing the data center environment (controlling dew points and the amount of outside air introduced in the DC) can minimize the risk. The corrosion sensors can also measure the effectiveness of air filtration in DCs and assess the time when air filters has to be changed.

1.2 Power sensors

To monitor the energy consumption in DCs, an accurate and non-intrusive power monitoring solution was developed based on Hall sensors. The power monitoring solution is suitable for dense monitoring of the power consumption at panel and distribution circuit levels. Furthermore, the power sensing solution could identify branch circuits to which the IT equipment is connected by analyzing the correlation between branch circuit and IT equipment power patterns.

The Hall sensor is embedded in a ferrite bead that clamps on the power carrying cable and is measuring the Alternating Current (AC) current. The signal is sampled at a rate of 60 data point/seconds and the root mean square amplitude of the current is determined numerically. Calibration was carried out for different gauge wires, commonly encountered in data centers, to calibrate the Hall sensor output versus the current in the cable. For power factor calculations, the voltage is also sampled in real time through electrostatic pickup by a wire running parallel through the ferrite bead. The fast sampling allows digital signal processing to determine the phase lag between the current and voltage signal. Signal processing and power factor calculations are carried out on the Signal Processing Board (SPB) and Collection Computer Board (CCB) (Fig 5).

Fig 5 Power sensors, power sensor board (7 sensors), the Signal Processing Board and the Collection Computer Board for real time power monitoring.

For installation of the power sensors, while avoiding power down of power panels, a new method was developed where an inexpensive clamp to install the ferrite on a cord can be used while wearing just protective gloves. The implementation and installation of the clamp and ferrite beads is illustrated in Fig 6. The power sensing data and the digital signal processing carried out on the CCB board are integrated with MMT server. The technology was tested in two DCs and demonstrated a better sensitivity than existing power monitoring solutions, at a fraction of cost.

Fig 6 Sensor and clamping approach of the ferrite beads on a power cable.

2. MMT Modeling Technologies

2.1 Computational Fluid Dynamics modeling

Current state-of-the-art numerical modeling approaches in DCs rely on the use of computational fluid dynamics (CFD) models based on solving the Navier-Stokes equations for air flow coupled with an equation for heat transfer. While this approach has been successfully used and is the most accurate modeling technology, especially for planning purposes, it comes with long calculation times, making it unsuitable for performing (near) real-time simulations. In addition, it is often not clear whether the quality of the modeling input data warrants such detailed or time-consuming computations. Hence one of the focus areas within MMT has centered on the development of simpler and, computationally speaking, faster CFD models for air and heat transfer, thus leveraging the fact that the availability of real-time measurement data could be “traded” against the complexity of the partial differential equations comprising the model. Real-time sensor measurements, which provide information about current (i.e. realistic) conditions in a data center, are used to define the required input information, mainly in the form of boundary data for the boundary value problems defining the models.

The MMT deployment at a Video Hub Office (VHO) provides a useful example of the value of the analytics in MMT for predicting changes in cooling resources. After analyzing the real time environmental data, it was determined that there was more cooling capacity in that facility than needed. It was recommended that the VHO would have plenty of cooling capacity even with one of the four ACU’s turned off. In order to see how the environment might change under these conditions, an underutilized ACU unit was virtually ‘turned off’ in the MMT client software. The simulation of 3 ACU operating was compared with the experiment where the ACU was shut down. With all four ACU’s on, the cooling zones are as shown on the left (Fig 7). The middle figure

show the simulations result when one ACU is turned off and the cooling zones merge from four to three zones. The right figure shows the cooling zones using the analytics on the real time data after that ACU was turned off in the facility. The prediction and the actual results are overlapping demonstrating the accuracy of the modeling.

Fig 7 Simulations of the cooling zones before and after MMT implementation.

2.2 Statistical Thermal Zone Mapping

In the statistical work, a knowledge based models and trends were developed and combined with Kriging techniques. A comprehensive knowledge base of thermal profiles has been generated from MMT data of over 80 DCs showing s-shaped, vertical temperature profiles across the server inlets of a rack (Fig 8). Analysis of extensive temperature profiles has shown that the form of s-shape is governed by physical parameters such as air flow supply and demand, discharge temperatures of the neighboring ACUs, the relative location with respect to ACUs and other servers. The statistical models can be used to estimate the temperature distribution in a DC under constant air flow conditions (Fig 9). The universality of the S-shaped temperature profile allows the extension of the statistical methods to any DC that use air cooling. The dynamic model was extended through regression analysis to forecast temperature profiles in the DC.

Fig 8 S-curve pattern for the vertical temperature profiles for ten different air conditioner settings. Ten solid curves are the MMT observations at ten settings and the dashed curves are the statistical model estimations

Fig 9 Statistical temperature fitting for different heights under fixed air conditioner setting. The top figures are the MMT temperature measurements where the bottom figures are the fitted temperature values.

A statistical method, which leverages temperature measurements from real-time MMT sensing system, is developed for assigning dynamically thermal zones. Such thermal zones are generally defined as the region of influence of a particular cooling unit or cooling "source" (such as an air condition unit (ACU)) and can provide valuable decision support for optimizing cooling. In order to characterize ACU thermal zones, a statistical method was developed to model the correlations between temperatures observed from sensors located at the discharge of an ACU and the other sensors located in the room. Outputs from the statistical solution were used to optimize the placement of equipment in a data center (Fig 10), investigate the possible failure scenarios, and make sure that a proper cooling solution has been achieved.

Fig 10 Thermal zones in a Video Hub Office characterized by the correlation between each of the four ACU discharge temperatures and the temperatures in the room. It shows that ACU#1 has the largest impact in its closer vicinity and ACU#1 and ACU#4 have significant larger thermal zones than ACU#2 and ACU#3.

2.3 A Spatio-Temporal Prediction Model

A spatio-temporal model was developed to predict the temperature distribution of a DC for future time (forecasting) at any locations. The spatio-temporal prediction model can be used for “what-if” analysis for energy efficiency improvement. The “what-if” analysis capabilities are demonstrated through an air-flow optimization study (Fig 11) for the VHO where temperatures are forecasted around the IT racks. Based on temperature forecast (Fig 11) a dynamic workload allocation can be implemented based on the thermal profiles of the DC.

Fig 11. Temperature distribution prediction for the next time stamp.

3. Software Development

A ‘cloud-ready’ analytics repository platform was developed that can be used independent of the specific hardware platform. The MMT software was extended to include: (1) an improved and more customize-able alarm system, (2) MMT reporting, (3) corrosion analytics, (4) real time CFD simulations, and (5) ACU controller.

A fully automated CFD analytic module embedded in MMT was developed that requires no user interventions and would run either as a real time simulation or as a “what-if” module to predict the data center response. The CFD model takes into account the physical DC layout, rack placement, and sensor distribution. The module will generate either a 2D or a 3D mesh and the solver will set-up the problem and will start the execution for CFD simulations. The simulations leverage the existing modeling capabilities based on reduced order sensor response and will run in less than 2 seconds computational time for a 50 kft² DC. The CFD based modeling capabilities can create temperature, dew point, and plenum pressure modeling and simulations of CRAC thermal zones, tile flow, tile cooling power and CRAC set-point temperature optimization. A CFD simulation of thermal zones and CRAC thermal zones is shown in Fig 12.

Fig 12 MMT interface for CFD simulation of temperature and cooling power distribution in a data center.

A series of real-time “what-if” optimization algorithms for DC have been developed and implemented into the MMT software. For a given cooling configuration (which is being measured and characterized in real-time using MMT) an optimization algorithm allows identifying the optimum placement of new servers (or workloads) or alternatively where to remove servers or to remove workload. Another optimization algorithm optimizes performance of the data center without creating hotspots. The optimization uses a physical model combined with linear and quadratic programming algorithms as well as linear and non-linear least square fitting (with or without constraints). The optimization result for optimum workload displacement to obtain best performance without creating hotspots for a given total power is shown in Fig 13. The two images correspond to different cooling conditions in the DC.

4. Commercialization

The corrosion sensor technology that was developed under this program has a couple of unique features: (1) 7 year lifetime for sensor at a corrosion rate of 300 Å/month, (2) sensitivity better than 1 Å in thickness change, and (3) a field replaceable sensor. Corrosion rate calculation algorithms were implemented in MMT based on moving average algorithm. The corrosion sensors and analytics are fully compatible with MMT.

The corrosion solution was proposed for licensing to business partners: (1) companies that are commercializing gaseous filter solution where the corrosion sensor will ensure that filtration effectiveness and (2) companies that are manufacturing ACU units to be used in air side economized DCs. The corrosion sensor and management solution were evaluated by the business partners interested in licensing the technology. We furthermore conducted “round robin” tests where existing corrosion sensing technologies were compared side by side to validate IBM’s corrosion sensing performance. There are ongoing discussions with two air filter manufacturing companies and also one ACU manufacturing company for corrosion sensor licensing.

Fig 13 Optimization of workload placement for a data center with a given cooling capacity.

For power monitoring solution a licensing agreement with power distribution companies is considered. The power sensing technology has unique features (small size, accuracy, non intrusive monitoring, possibility to mount them on “live” power line) and functionality that allow the current power sensor design to be added to existing power monitoring solution that exist on the market. Presentations were made to two of the global companies and negotiations are currently underway for the rights to the intellectual property covered by the patent applications filed under this project with at least one of the companies.

5. Benefit Assessment

Energy efficient technologies could significantly improve the performance for existing or newly developed DCs. From the field tests it was demonstrated that MMT can achieve a 20% to 40% reduction in energy used for cooling, by implementing various technology components and best practices. A list of technologies and associated benefits are shown in Table 2.

Feature	Benefits	Savings
Real-time heat/humidity/ pressure/flow maps	<ul style="list-style-type: none"> • Prevents hotspots • critical for best practices' implementation 	3-5 %
Power Management	<ul style="list-style-type: none"> • Increases UPS utilization • Reduces “stranded” power 	2-5 %
Operational CFD support	<ul style="list-style-type: none"> • Improves planning and optimize DC layout 	3-4 %
Energy Efficiency Reporting	<ul style="list-style-type: none"> • Enables consistent management of energy efficiency 	5-8 %
Cooling Zones	<ul style="list-style-type: none"> • increases utilization of cooling infrastructure 	3-5 %
Air side economizer/ Corrosion Management	<ul style="list-style-type: none"> • Outside air economization • Improved reliability 	10-15%

Table 2 Achievable energy savings using MMT technology components.

The short and long term impact of MMT commercialization can be estimated for DC/TFs assuming that the technology is adopted by industry. In 2006 it was estimated that the total energy consumed by data centers to be 60 billion kWh (7 GW) [1]. An additional 18 billion kWh would be utilized by telecom facilities [4]. Assuming a 20% savings (see Table 2) applicable to 50% of the DC/TF can result in an instant of 8 billion kWh savings.

For long term projection, it is estimated that there were a total of 6400 data centers in 2006 and their number increases annually by 12 % [1]. It is also assumed that MMT will be compatible with 50 % of the newly built DCs with a starting deployment date of 2012. The assumption consider that in 2012, 5% of all newly built DC will adopt MMT and the adoption will increase with additional 5% each year until 2020 when it will reach a 50% adoption. Once a 50% penetration is achieved it will remain at that level from 2020 onwards.

In Table 3 the direct electricity displaced is calculated under the above assumptions and projected until 2035 assuming that a typical data center consumes 9.5 MWh (~1.1 MW). The possible cost savings for businesses are calculated based on MMT deployment (assuming electricity cost of 6 c/kWh).

Impact By year	2012	2015	2025	2035
Cumulative units installed	60	1223	12880	45300
Market penetration	5%	25%	50%	50%
Direct electricity displaced (billion kWh)	0.060	1.161	12.243	43.050
Energy cost savings (\$MM/year)	3.6	69.66	734.58	2583.2

Table 3 Economical benefit of adoption of MMT projected until 2035.

Adoption on MMT 2.0 in new data centers could be a game changer to improve the energy efficiency of existing and future data centers.

6. Accomplishments

6.1 Publications and Presentations

1. V. López and H. F. Hamann, "*Measurements-based modeling for data centers*", In Proceedings of the 12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), June 2010.
2. M. Cole, L. Hedlund, G. Hutt, T. Kiraly, L.J. Klein, S. Nickel, P. Singh, and T. Tofil, "*Harsh Environment Impact on Resistor Reliability*", SMTAI, Orlando, FL, 2010.
3. H. F. Hamann , V. López and A. Stepanchuk, "*Thermal zones for more efficient data center energy management*", In Proceedings of the 12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), June 2010.
4. R. Ghosh, and Y. Joshi, " *Dynamic Reduced Order Modeling of Convective transports in Data Centers*" at NSF I/UCRC meeting, Binghamton, New York, December 2010.

5. H. Li, H.F. Hamann, "A Statistical Approach for Thermal Zone Mapping", InterPack, July 2011.
6. V. López and H. F. Hamann, "Heat transfer modeling in data centers", International Journal of Heat and Mass Transfer, Vol. 54, pp. 5306–5318, 2011.
7. V. López and H. F. Hamann. "A numerical technique for the approximation of thermal zones", InterPACK 2011. July 2011.
8. S. Yarlanki, R. Das, H. F. Hamann, V. Lopez, A. Stepanchuk, "Employing Thermal Zones for Energy Optimization in Data Centers", InterPack, Proceedings of the ASME 2011 Pacific Rim Technical Conference Exhibition on Packaging and Integration of Electronic and Photonic Systems, MEMS and NEMS, 2011.
9. R. Das, S. Yarlanki, H. Hamann, J. O. Kephart, V. Lopez, J. Lenchner, "A unified approach to coordinated energy management in data centers", CNSM 2011, 7th International Conference on Network and Service Management, Paris, France, Oct. 24-28, 2011.
10. W.El-Essawy, A. Ferreira, J. Rubio, M. Ware, K. Rajamani, M. A. Schappert, and H. Hamann, "Smarter Data Center Power Monitoring and Management", SenSys '11 Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems , 2011.
11. R. Ghosh, V. Sundaralingam, S. Isaacs, P. Kumar, and Y. Joshi, "Transient Air Temperature Measurements in a Data Center", ISHMT conference, Chennai, India, Dec. 2011
12. R. Ghosh, V. Sundaralingam, P. Kumar, and Y. Joshi, "Experimental Characterization of a Data Center Facility", ISTP-22 Conference, Delft, The Netherland, Nov. 2011.
13. R. Ghosh, and Y. Joshi, "Dynamic Reduced Order Thermal Modeling of Data Center Air Temperature", ASME InterPack 2011 Conference, Portland, USA, 2011.
14. W. El-Essawy, A. Ferreira, J. Rubio, T. Keller, M. Ware, K. Rajamani, M. Schappert and H. Hamann, "Demo: Smarter Data Center Power Monitoring and Management", SenSys'11, 2011
15. V. López and H.F. Hamann, "Data center metrology and related modeling techniques", Presentation at the International Congress on Industrial and Applied Mathematics (ICIAM), Vancouver, BC, Canada, 2011.
16. W. Huang, M. Allen-Ware, J. B. Carter, E. Elnozahy, H.F. Hamann, T. Keller, C. Lefurgy, J. Li, K. Rajamani, and J. Rubio, "TAPO: Thermal-Aware Power Optimization Techniques for Servers and Data Centers", International Green Computing Conference (IGCC), **Best Paper Award, 2011.**
17. L.J. Klein et. al, "Humidity control and dew point management", ASME InterPack 2011 Conference, Portland, USA, July 2011.
18. L.J. Klein at al, "Corrosion management for Data Centers", Semitherm 2011.
2. H. Jiang, X. Deng, V. Lopez, H.F. Hamann **(Invited)** "Online Computer Model Updating and Forecasting with Applications to Data Center Thermal Management", The International Conference on the Interface between Statistics and Engineering (ICISE), 2012.
19. V. Lopez, H.F. Hamann, H.Jiang, and X. Deng, "Mathematical Modeling with Sensor Data", SIAM Conference on Mathematics for Industry, 2012.
20. S. Yarlanki, B. Rajendran, and H. Hamann, "Optimization of $k-\epsilon$ turbulence model for a data center using Neural Networks", ITherm 2012: Thirteenth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, 2012.
21. L. J Klein, M. Schappert, H. F. Hamann, "Corrosion Risk Management in IT Facilities", Itherm 2012, May 2012.

22. L. J. Klein, Sergio Bermudez, Hans-Dieter Wehle, Stephan Barabasi, H. F. Hamann, *"Renewable Energy Powered Data Centers"*, Semitherm 2012.
23. H.F. Hamann and V. López, *"Data Center Metrology and Measurement-Based Modeling Methods"*, **Book chapter** in Energy Efficient Thermal Management of Data Centers, Y. Joshi and P. Kumar (eds.). Springer. March 2012.
24. R. Ghosh, V. Sundaralingam, and Y. Joshi, *"Effect of Rack Server Population on Temperatures in Data Centers"*, ITherm 2012.
25. W. El-Essawy, A. P. Ferreira, J. C. Rubio, T. Keller, K. Rajamani, M. Ware, and M. Schappert, *"Managing a Forest Means Measuring Trees: Enabling Data Center Real-Time Energy Management"*, IEEE Transactions on Computers, 2012.

6.2 Patents/Disclosures

- D. Manzer, L. Klein, *"Real Time Numerical Computation of Corrosion rates from Corrosion Sensors"*.
- L. Klein, F. Marianno, H. Hamann, *"Air conditioning filter replacement lifetime prediction and implementations"*.
- R. Das, H. F. Hamann, V. Lopez, A. Stepanchuk, S. Yarlanki, *"Provisioning Cooling Power and workload to optimize utility of cooling units and processing resources within a data centers"*.
- S. Yarlanki, H. Li, A. Stepanchuk, H. Hamann, *"Real-time modeling of heat distributions"*.
- G. Carpenter, W. El-Essawy, A. Ferreira, T. Keller, J.C. Rubio and M. Schappert, *"Non-Contact Current and Voltage Sensor"*.
- V. López, H. Hamann. *"Techniques for Determining Physical Zones of Influence."*
- H. Li, H. Hamann, *"Data Center Thermal Management"*.
- L. Klein and H. Hamann, *"Corrosion device for universal assessment of pollution in data centers"*
- L. Klein, H. Hamann, *"Forecasting and managing corrosion in energy intensive facilities and high tech buildings"*.
- H. Hamann, H.-D. Wehle, S. A Bermudez, A. Stepanchuk, *"Method for evaluating optimum Data Center Operation"*
- H. Hamann, S. A Bermudez, H.-D. Wehle, *"Server Rack for improved Data Center Management"*
- S. A Bermudez, H. Hamann, F. J Marianno, *"Method for Early Detection of Cooling-Loss Events"*

Conclusions

A scalable and comprehensive energy efficiency solution was developed that drastically improves the energy efficiency in data centers and telecom facilities. The MMT platform was extended with a new set of sensing solutions; wireless sensor network, corrosion sensors, and power monitoring. The sensing solution can be leveraged to minimize power loss, to eliminate the risk due to accidental pollution from outside air, or failure risk due to higher temperature operation of data centers. The modeling and statistical tools offer real time operational support and can be used for “what if” scenarios; to optimally allocate the workload on IT servers, optimal placement of an IT rack in a data center, and ACU control. These tools broadly applied can reduce energy consumption with up to 30% as was demonstrated at field test sites.

The technologies developed under this grant were benchmarked to demonstrate their robustness and scalability. It was demonstrated that MMT recommendation can results in a DCIE of 87 %, one of the best performances in industry. All the developed technologies are unique in sensitivity, reliability, and accuracy and offer a clear market advantage for any commercial entity that would license the technology. Discussions are ongoing with business partners to commercialize the technologies and to deploy them at large scale to enable energy efficiency implementations, power monitoring, and air side economizations.

Appendix A

This section contains the detailed description for the DC energy efficiency factor obtained for IBM's Green Data Center in Poughkeepsie. The DC has a surface area of 1100 ft² and was built in 2009 for hosting IT equipment. The energy intensity of DC is 3407 kBtu/ft²/yr and the estimated Green House Emission is 945 MTCO₂/year. The DC meets all the industry standards for indoor environmental conditions: (1) Ventilation for Acceptable Indoor Air Quality as recommended by ASHRAE Standard 62, (2) acceptable thermal environmental conditions as specified by ASHRAE standard 55 for thermal comfort, and (3) adequate illuminations as specified by IESNA Lighting Handbook for lighting quality.

The DC contains 8 racks with IT equipment and one ACU unit. The server infrastructure was : Nine BladeCenter, Fifty System x rack mounted servers, two IBM Power 570 (POWER6) rack mounted servers, one IBM System z9 and z10, IBM TotalStorage racks.

The thermal baseline of the DC was assessed using MMT sensor platform. The thermal scans at two different heights (0.5 ft and 5.5 ft) reveal that a significant portion of the DC has elevated temperatures (Fig 14).

It was established that in more than 8 locations, the rack inlet temperature was higher than the ASHRAE recommended upper temperature value of 80 °C. Additionally, the MMT scan established that:

- (1) ACU utilization was 77 %. This metric was measuring the ratio of heat removed by the ACU over the nominal ACU removal capacity
- (2) The targeted air flow was 83%. This metrics measure the percentage of air from ACU that is passing through the perforated tiles.
- (3) Air recirculation caused the hotspots formation at the inlet of 8 racks.

Fig 14 Thermal scan of the Poughkeepsie data center at 0.5 ft and 5.5 ft prior to optimization.

The MMT analysis was complemented by the CFD simulations to establish the air circulation for best rack placement and to establish the spaces where additional servers can be deployed. After determining the cooling capacity, it was decided to use rear door heat exchangers for cooling, to remove the heat from the high density rack. There are several reasons for using water for cooling to support the additional IT load. Water is 3,500 times more efficient than air at removing heat, and the Cooling Distribution Unit (CDU) that supports the rear door heat exchanger uses less energy than an ACU. With the additional cooling capacity it was determined that additional equipment can be added to the DC. The detailed energy use before and after MMT recommendation implementation is shown in Table 4 (the highlighted areas represent actual measurements). After optimization, the IT power almost doubled while the cooling power was just marginally increased.

Power (kW)	Start	After optimization	Using water cooling
IT	52.73	91.73	91.73
CRAC	4.56	5.1	5.1
CDU	0	2.6	2.6
Lighting	1.19	0.3	0.3
Other	0.82	0.82	0.82
Data center total	59.3	100.55	100.55
Facilities	11.79	20.0	4.57
DCIE	0.74	0.76	0.87

Table 4 Power measurements before and after MMT optimization. The column “Using water cooling” was achieved when water from the Hudson River was used for back door water cooling of the servers.

In Table 4, the back door water cooling was used for the case and “Using water cooling”. The racks were cooled with water from the Hudson River in the case of “Using water cooling”. This was possible once the river temperature was below 43 °F and the chiller was turned off and the pumps were used to just pump water.

The MMT thermal scan at 5.5 ft height after the MMT recommendations were implemented is shown in Fig 14. Majority of the hotspots are eliminated and the temperature variation across the DC becomes more uniform.

Fig 15 Thermal map of the data center after energy optimization.

To validate the data center infrastructure efficiency metrics the power consumption in the data center was measured for a whole year in accordance with US EPA recommendations [10]. The total consumed power and IT Consumed Power was measured at 15 minute interval. The data was aggregated in a monthly total power, the monthly consumed IT power, and the DCIE values was calculated based on the measured data (Fig 16).

Fig 16 Total energy, IT consumed energy, and DCIE variation over a 12 month period.

A DCIE metrics of 84% (averaged) was maintained in the data center over a 1 year period [11]. Since 2010, MMT technology is monitoring in real-time the DC performance.

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