CONSORTIUM for BUILDING ENERGY INNOVATION

REPORT

Title: **Automation and Demonstration of a Plug-and-Play (PnP) RTU Coordinator**

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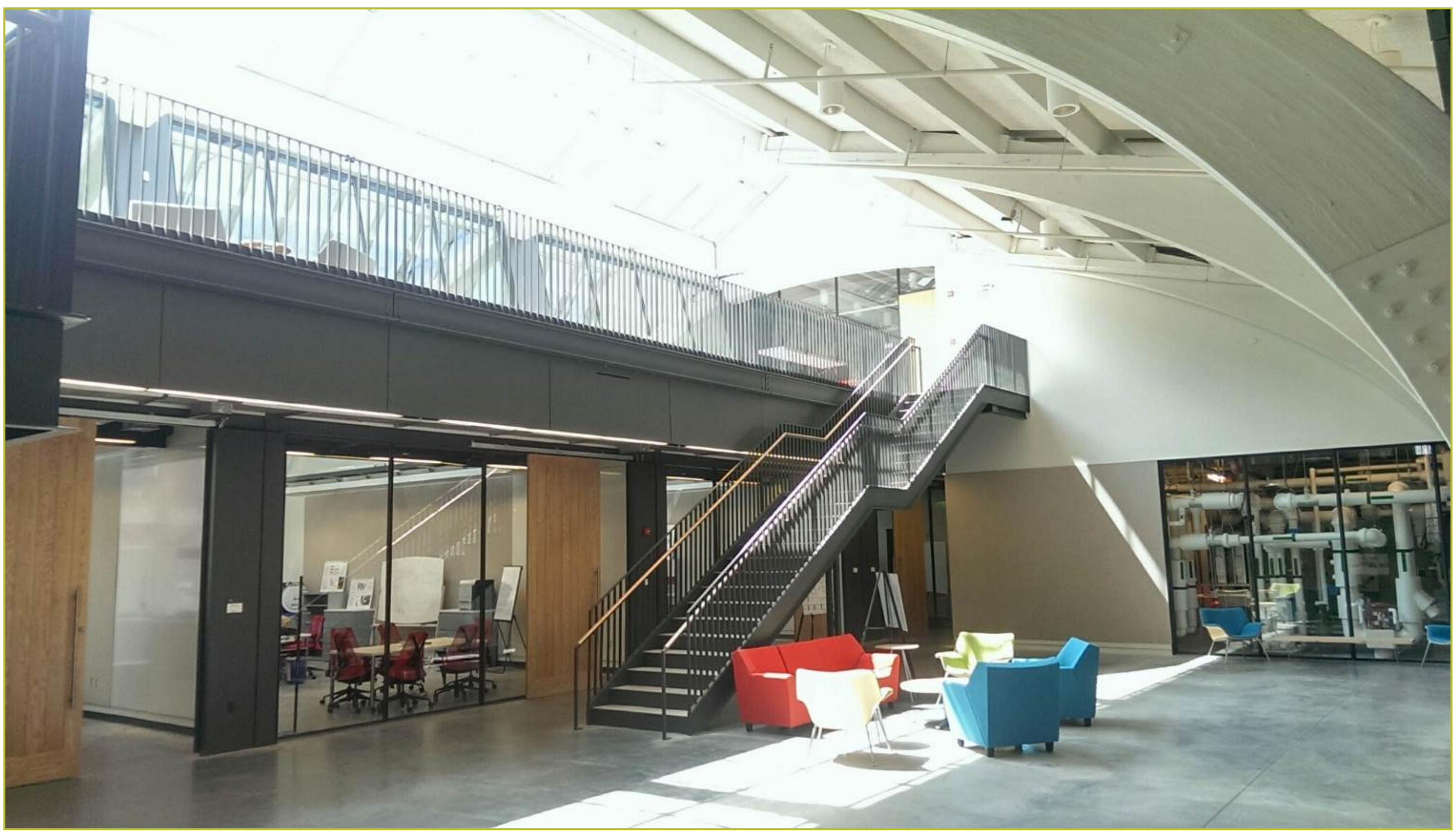

Report Abstract

In a previous budget period (BP4), a basic control algorithm was developed that coordinates the operation of multiple RTUs for small/medium commercial building applications with the goal of controlling on/off staging of multiple rooftop HVAC units (RTUs) so as to maintain comfort while minimizing energy consumption and peak electricity demand. The algorithm is termed "plug-and-play" because the thermostat response models and optimization require only minimal configuration and no additional sensors for implementation.

For this BP5 project, the goal was to demonstrate and evaluate a practical business case for implementation of the RTU Coordinator across multiple locations. At the start of this budget period, our plan was to consider Bank of America (BoA) buildings across the country and determine the 10 most promising sites for implementation and demonstration. The typical processes for DOE High Impact Technology (HIT) demonstrations were reviewed and utilized in creating rigorous criteria and a methodology for selecting demonstration sites. First of all, we established pre-filtering criteria to down-select from about 3300 sites to nearly 150 sites. We then used minute-by-minute data collected from the remaining sites to build models that were used to assess the estimated savings associated with implementing the PnP controller. Simple economic payback periods were determined and utilized to select the 10 most promising sites. On average, 22% energy savings and 15% peak electric demand reduction were estimated for implementation of the RTU coordinator at these sites with economic payback periods of less than 2 years. The processes and final sites are described in detail in Milestone Report 2.1.b. The current report provides a brief summary of the simulation analysis and savings results for the down-selected sites.

The BoA buildings utilize a standardized Niagara-based energy management system (EMS) and a typical site has a single Java-based JACE-2 site controller. A complete implementation strategy was developed based on this architecture and is summarized in Milestone Report 2.1.c. During the course of this project, management of the facilities transitioned from an internal BoA function to an outside vendor. Numerous efforts were made to obtain permission to implement the PnP at the selected sites, but bank security issues prevented implementation within a timely manner. As a result, we identified alternative demonstration sites through existing customer relationships and using the criteria developed for the BoA sites. Fourteen demonstration sites were identified and the PnP algorithm has been fully implemented at 10 of the sites as of the date of this report. We have preliminary results for these 10 sites and will continue to collect data over the coming months for 14 sites. During implementation at these sites, we were able to leverage the software developments related to the BoA sites. Approximately half the demonstration sites employ a Niagara, JACE-based EMS solution, whereas the other sites employ web-enabled thermostats with an open API.

This report provides a summary of the PnP algorithm, a description of the savings estimates for previous PnP evaluations, a description of site selection processes and savings results for the BoA sites, and a description of the final demonstration sites, implementations and preliminary results.

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1. INTRODUCTION

In many small/medium commercial buildings including a large percentage of retail stores, restaurants and factories, several rooftop HVAC units ('RTUs') share the job of cooling for non-partitioned areas. But large open spaces served by multiple RTUs can pose significant control challenges, such as spatial comfort variations and short-cycling of units. Furthermore, most such buildings lack EMS systems, so the need to add more sensors makes it costly and difficult to implement advanced energy controls.

A conventional ('CONV') solution for this situation relies on local feedback control, where a dedicated thermostat located in the vicinity of its supply diffusers controls each RTU. This can lead to poor coordination among the RTUs where some units carry the majority of the load; some units cycle on and off very frequently while others operate infrequently. Due to these challenges, there have been very few advanced control algorithms developed for these buildings despite their wide range of application.

The goal of the previous project (BP4) was to develop and perform limited demonstrations of a practical control algorithm for on/off staging of multiple rooftop units (RTUs). The controller aims at reducing energy consumption and cycling with low sensor requirements for RTU coordination. Termed *plug-and-play* (PnP), it was designed to minimize configuration time, leading to a more cost effective control implementation and successful market penetration for small/medium commercial building applications.

In BP4, the RTU Coordinator showed significant savings in HVAC energy use (15%) and peak electric demand (30%) for cooling compared to conventional controls, with equal or better thermal comfort. The BP5 project aimed to evaluate the business case for RTU Coordinator implementation across a wider range of sites. Purdue carried out this work in collaboration with Field Diagnostic Services, Inc. ('FDSI') to help bring this controls solution to market and gain a better understanding of likely market potential.

This BP5 project had two main parts: 1) Estimate savings opportunities for multiple Bank of America (BoA) sites using existing data; 2) Implement and evaluate the performance of the RTU Controller at a variety of demonstration sites. In section 2 of this report, we summarize the RTU controller and our assessments of the controller from earlier efforts. Section 3 describes the processes and results associate with savings estimates for BoA sites. Finally, section 4 describes the field demonstration sites and example evaluation results.

2. RTU COORDINATOR: SUMMARY AND PREVIOUS SAVINGS ESTIMATES

2.1. Overview of RTU Coordinator

Figure 1 shows the basic control structure of RTU Coordinator. It takes the standard form of an adaptive controller, but requires no measurements beyond thermostat temperatures and on/off output signals.

Implementation of the RTU Coordinator does not require climate, weather or other data (e.g.: plug load). Instead, all unknown disturbances, which could influence future temperature prediction, are modeled from the available measurements. This modeling approach was validated with data sets from several buildings; using only minimal sensor information, accurate models (e.g.: ~0.5 oC standard deviation of 1 hr.-prediction errors) were estimated for all sites.

Eliminating additional sensors is an important feature of the RTU Coordinator, as it implies reduced capital and maintenance costs, and thus an expanded range of applications. The control objective is to minimize HVAC energy consumption and reduce compressor cycling while meeting comfort constraints. In previous work, it was shown that the RTU Coordinator control algorithm can also significantly reduce peak electric demand.

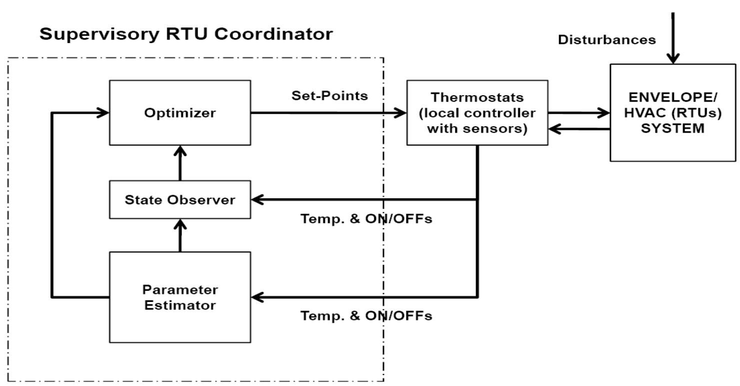

Figure 1: Basic structure of the proposed supervisory RTU coordinator

2.2. Previous evaluation of RTU Coordinator

Initial estimates of the potential for energy and demand savings potential were based on two case studies: a small sit-down restaurant (Harvest Seasonal Grill) near Philadelphia, PA and a gymnasium (Central Baptist Church) located in Knoxville, TN. Both buildings are characterized by large, open spaces served by multiple RTUs with individual thermostats.

Harvest Grill site

Fig. 2 shows the RTU layout and floor plan of the Harvest Grill ('HG') restaurant. Four RTUs serve the dining area; numbers 1 - 4 indicate the locations of their supply diffusers. The colors associated with the 4 numbered zones connect each set of supply diffusers (solid circles) with the associated thermostats (open circles) and RTUs (solid rectangles). All un-numbered areas are within the kitchen, which was not considered for this case study.

As shown in the diagram, please note that the thermostats controlling RTUs 2 and 4 are closely coupled to supply air from the diffusers for RTUs 1, 2, and 4. It should also be noted that RTU 1 is a 2-stage unit; at 15 tons it has about 3 times the cooling capacity and 35% higher efficiency of the other three, single-stage RTUs 2, 3, and 4 (each rated @4 tons). The total number of degrees of freedom for control of RTU staging for HG is 5.

<u>Central Baptist Church gym site</u>

Fig. 3 shows the RTU layout and interior floor plan of the Central Baptist Church ('CBC') gymnasium. There are four identical two-stage RTUs that serve different quadrants of this rectangular open space. Each thermostat is located on an outside wall, adjacent to the associated RTU. The CBC gym has Modbus thermostats with a 0.1° F resolution; there are 8 degrees of freedom to be used in our staging controls for these units.

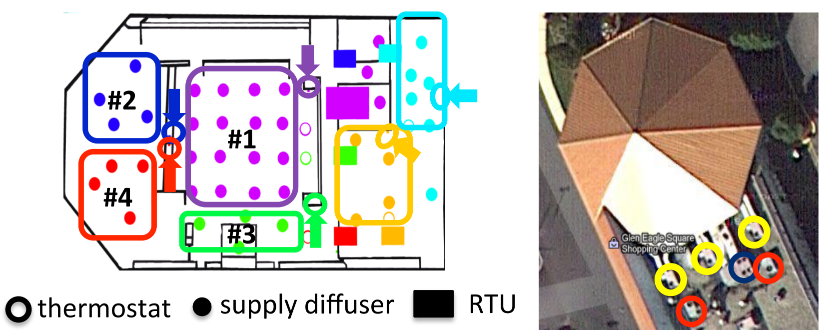

Figure 2: Location of supply diffusers and thermostats for various RTUs at Harvest Grill

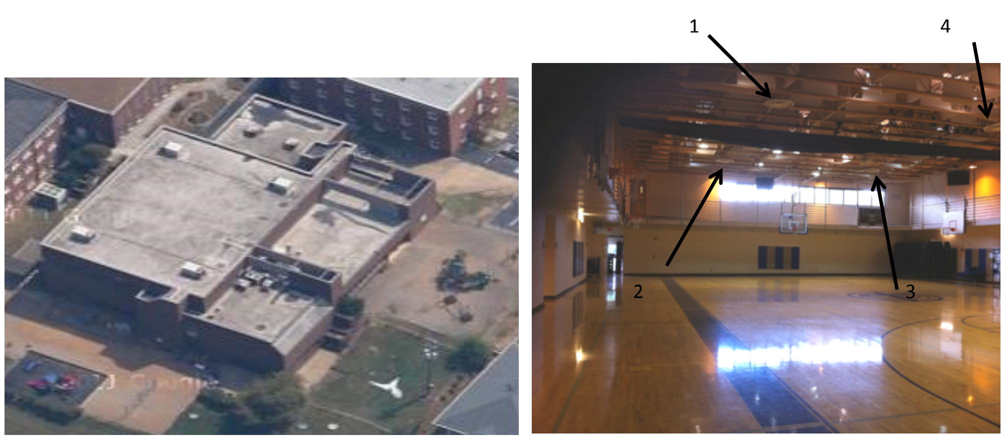

Figure 3: RTUs and supply diffusers at Central Baptist Church gym

Input-output response models were trained for both sites; a variety of different models and training approaches were investigated. The resulting models were implemented within the RTU Coordinator control algorithm in order to modify the cycling behavior of the units to minimize power consumption over the next hour. For the CBC gym case study, the control strategy was switched between conventional control (each RTU independently controlled) and the RTU coordinator over a period of a week.

Tables 1 and 2 show results from this test period, comparing RTU coordinator vs. conventional controls in RTU electrical energy savings, RTU peak demand power (15-min. moving avg.) and comfort violations. The CBC RTUs are identical, thus primary efficiency opportunities are a result of reduced cycling. Energy savings were small, but demand savings were substantial and less cycling would lead to increased equipment life. Maximum deviation from the set-points was also reduced.

Table 1. RTU energy savings and peak power reduction with RTU Coordinator (CBC gymnasium)

	% Energy Savings	**% Peak Power Demand Reduction (15min MA)**
RTU Coordinator	8.2%	42.6%

Table 2. Maximum deviation from thermostat set-points, RTU Coordinator vs. conventional control (CBC gymnasium)

	Conventional	**RTU Coordinator**
Max. Comfort Violation	2.5^{o}F	1.2^{o}F

At the HG site, a greater range of RTU efficiency offered more opportunity for energy savings. We developed a reduced-order CFD and envelope building model that accurately predicts thermostat responses to RTU cycling; this was coupled to RTU, building envelope and thermostat models. The RTU coordinator was implemented within the simulation environment and energy savings relative to conventional control were evaluated.

Table 3 presents average energy usage per day for the four HG RTUs, comparing the results from RTU Coordination vs. conventional controls. Energy savings of more than 20% were achieved through increased operation of the larger, more efficient RTU 1 (c.f.: Figure 2). In addition, short cycling was reduced and comfort conditions were maintained roughly equivalent to those found when employing conventional controls.

Table 3. RTU Electrical usage per day, RTU Coordinator vs. conventional control (Harvest Grill restaurant)

Method	Energy consumption [kWh/day]
Conventional	362.3
RTU Coordinator	281.7 (22.2% less than conventional)

3. EVALUATION OF SAVINGS OPPORTUNITIES FOR BANK OF AMERICA SITES

Investigating distributions of energy and demand savings of the RTU Coordinator over multiple sites is important in evaluating its likely market potential. Purdue collaborated with Field Diagnostic Services, Inc. (FDSI) in carrying out an extensive evaluation for Bank of America sites.

Since 2009, FDSI has partnered with Bank of America ('BoA') in design and implementation of the bank's EMS (Energy Management System), to improve comfort and save on energy costs. Their EMS collects site data, the resulting database allows us to estimate distribution of energy savings and peak demand reduction for many BoA sites via on simulation evaluation.

3.1. Evaluation process for RTU Coordinator performance

After pre-filtering of the sites (see Milestone Report 2.1.b), the following approach was used to assess potential benefits of RTU Coordinator implementation for nearly 150 sites:

1. Develop a simulation model ('virtual test bed') based on collected data for each site.
2. Using the virtual bed, test for HVAC energy, peak demand & utility costs.
3. Compare results for RTU Coordinator vs. conventional thermostat control algorithm.
4. Evaluate simple payback periods for RTU Coordinator vs. conventional control.

The test bed was composed of building envelope and HVAC models derived for each BoA site, using the available data. The building envelope model uses outdoor air temperature and lighting runtime as inputs that characterize heat gain sources, with RTU run time fractions

(‘RTF’) as control inputs. See Milestone Report 2.1b for more details on the model-building methodologies.

Once the model for each site was developed, we ran the two control algorithms within the virtual test bed using the same evaluation dataset, i.e. NOAA data and historical lighting schedule. Performance was evaluated using the following metrics:

1. Energy savings (cooling)
2. Peak demand reduction (cooling)
3. Utility cost savings (cooling)
4. Simple economic payback period
5. Comfort violations vs. conventional control

Fig. 4 shows the process; all steps in this flowchart were repeated for each site. To calculate a simple payback period, each simulation was performed from 1 April to 31 November.

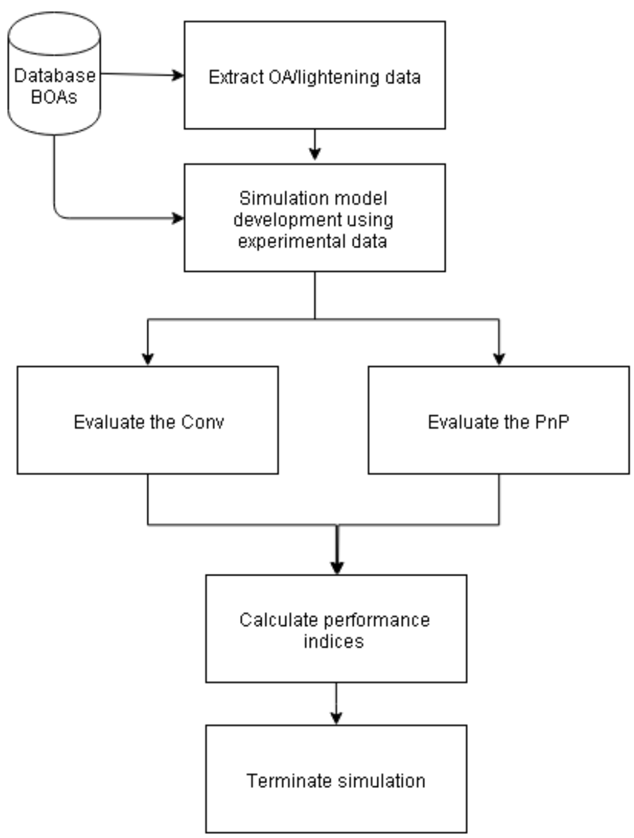

Figure 4: Process to estimate savings of RTU coordinator

3.2. Assessment of RTU Coordinator savings for BoA sites

Conventional control logic was used as a baseline for evaluating performance of the RTU Coordinator. Conventional controls used thermostats with a deadband of 0.5°F. All simulations employed NOAA outdoor air temperature for the cooling season (1 April to 31 Nov.) with set-points of 72°F (occupied) and 80°F (unoccupied). All simulations were based on experimental data as described in Milestone Report 2.1.b.

Sample of simulated test-site results

A sample result comparison between the two controllers for a site located in California is shown in Fig. 5. The sample period is 2014/10/12 and 2014/10/13. The test site is served by 5 RTUs controlled by individual thermostats; all five units have single-stage compressors. Our building envelope model showed significant couplings between spaces served by the RTUs.

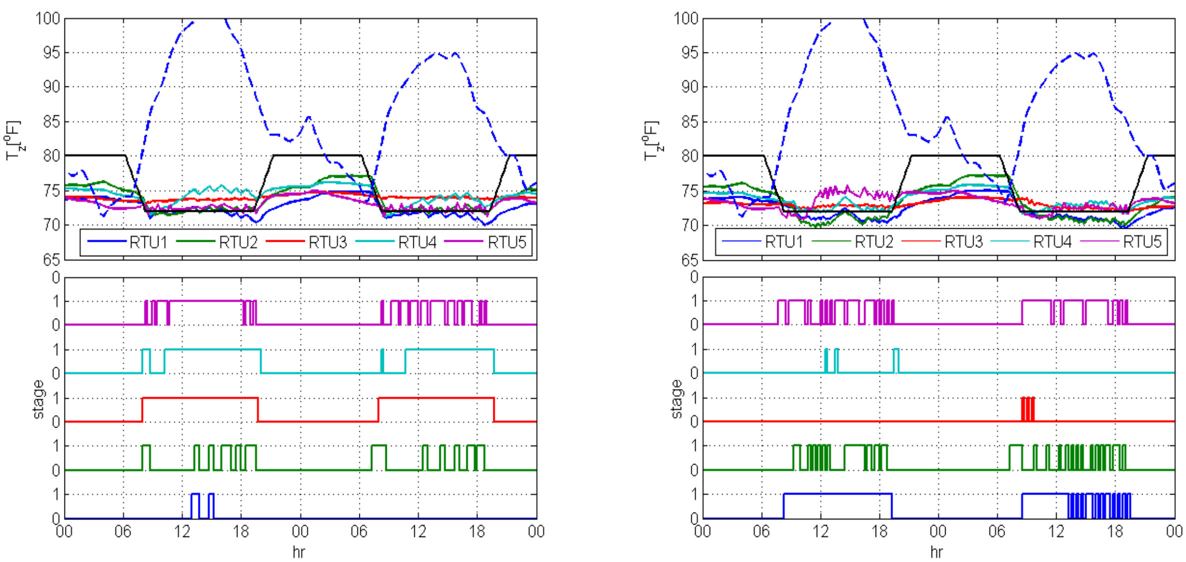

Figure 5: Sample comparison of results for conventional control logic vs. RTU Coordinator (simulation)

Fig. 5 compares responses of conventional control logic (left) and the RTU Coordinator (right). The upper figures represent zone air temperatures, set-point (black thick line) and outdoor air temperature (blue dashed line). The 5-zone air temperatures are marked with different colors and the stage profiles associated with the zone air temperatures are marked with the same color in the bottom figures.

Comparing the two sets of graphs, the thermostat temperature fluctuations are similar. However the run time fraction (RTF), defined as fraction of ON period to total period, differ significantly. Note the low RTF of RTU1 and 2, and the high RTF of RTU3 and 4 for the conventional control.

On the other hand, the RTU Coordinator behaves in a quite different manner; the figure at upper right shows that temperatures corresponding to RTU3 and 4 can easily be maintained despite low run-times for those two units. RTU1 is used much more and it shows strong inter-zonal coupling to the surrounding zones.

Indeed, our estimated building envelope model showed that RTU3 and 4 are very inefficient for cooling. Thus, by using the least efficient units less often, the RTU Coordinator showed about 20% energy savings vs. conventional control logic -- an observation that matches our simulated and experimental results from previous work.

Summary of savings estimates for multiple sites

The most promising 10 BoA sites were selected based on simulated results for the Apr./Nov. cooling season. They are summarized in Table 4; the ordering is based on utility cost savings [$/year]. In the calculation of the utility cost reduction, for purposes of this simulation, it was assumed that cooling loads from December to March were negligible at the sites chosen.

The total RTU power in the first column of the table is the sum of (estimated) rated RTU powers for all units, including compressors and fans. The number of installed units for each selected site is shown as 'RTU qty.'. Energy savings and peak demand reduction shown in the table are monthly averaged values, calculated over the simulation period (8 months; 1 April through 31 November).

Utility rate information was obtained from the electricity supplier for each site. For some sites where the information was not available, $0.1/kWh and $8 kW were assumed for energy and peak demand charges. When calculating payback periods for the selected 10 sites, we used the following assumptions.:

- Initial configuration: $500/site
- Server maintenance: $12/year/site
- Monitoring and maintenance: $150/year

Box plots in Fig. 6 (at left and right) show energy savings ('ES') and peak demand savings ('DS') for the 10 'most promising' sites and a randomly selected 30 sites. On each plot, the median is at center, 25th and 75th percentiles at the edges. The RTU coordinator shows average energy savings and peak demand reduction of approx. 25% and 15%, respectively, for the 10 'most promising' sites and about 15% for the 30 sites.

Because these buildings (banking centers) are relatively compact, absolute utility cost savings will be small despite significant percent savings potential shown for the RTU coordinator. Most of the (pre-filtered) BoA sites show RTU power consumption of less than 30kW. Nonetheless, payback periods for the 'most promising' 10 sites are less than 2 years.

Table 4: Summary of estimated savings (energy, peak demand and utilities) for 10 most promising BoA sites

Site ID	RTU qty.	Total RTU power [kW]	Energy savings [%]	Peak demand reduction [%]	Utility cost savings [$/year]	Payback period (year)
AZ3-250	5	36	33	37	1236	0.47
FL8-032	4	22	26	7	1182	0.49
FL2-201	5	18	28	12	802	0.78
CA0-151	5	15	28	35	659	1.01
AZ6-114	5	15	24	13	614	1.11
CA0-238	5	14	23	15	573	1.22
FL5-496	5	23	15	13	524	1.38
AZ3-238	4	10	29	20	492	1.52
AZ3-149	3	22	13	9	474	1.60
AZ3-181	6	17	28	28	437	1.82

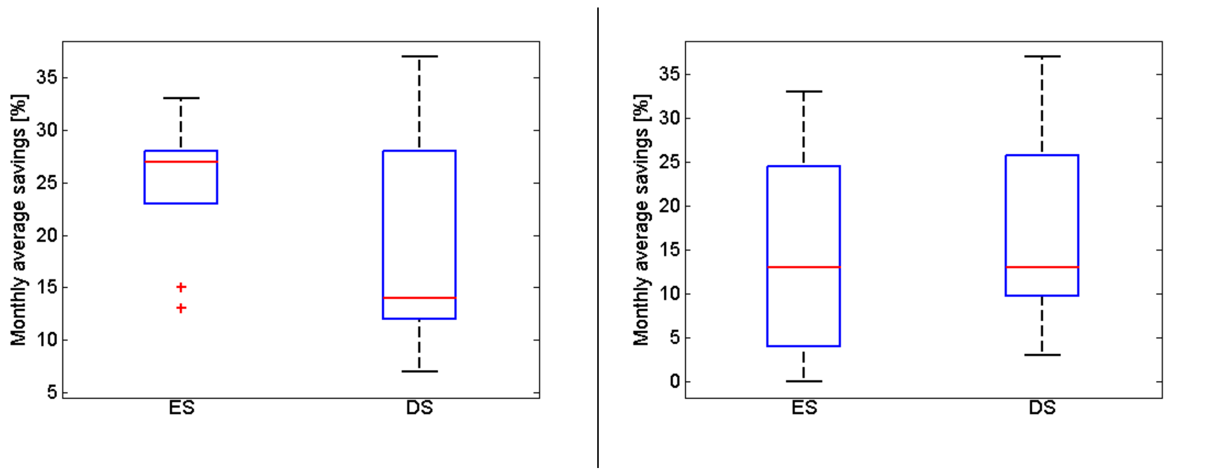

Figure 6: Estimated monthly average savings for BoA test sites. Left and right figures show results for the selected 10 sites and 30 sites, respectively.

We originally planned to implement the RTU Coordinator for the selected 10 BoA sites. Unfortunately, this plan became infeasible because management of building operations changed during the course of this project and permission was not granted for implementation. Instead, we partnered with FDSI to identify alternative demonstration sites through engagement with FDSI customers. The change from BoA to alternative demonstration sites moved quickly and a summary of the alternative demonstration sites is provided in the next section.

4. DEMONSTRATION OF RTU COORDINATOR

4.1. Brief description of demonstration sites

The PnP control and monitoring hardware and software have been installed in 10 demonstration sites that are listed in Table 5. Detailed information (e.g. name of a store, street address) has been omitted due to privacy concerns. Additional implementations at 4 other sites is underway and will be completed within the next month. The process of evaluating the RTU Coordinator will continue throughout the summer of 2016.

Table 5. Summary of 10 demonstration sites

Site (site ID)	# Units	City	State	Control platform
Small office building (LE)	4	Redlands	CA	Wi-Fi t-stat
Harvest Seasonal Grill	4	Glen Mills	PA	Wi-Fi t-stat
Fast food restaurant (11114)	4	Coral Springs	FL	JACE
Fast food restaurant (10934)	4	Pembroke Pines	FL	JACE
Fast food restaurant (19893)	3	Fort Lauderdale	FL	JACE
Small retail store (0113)	4	Orlando	FL	Wi-Fi t-stat
Small retail store (0212)	4	Orlando	FL	JACE
Small retail store (1014)	4	Altamonte Springs	FL	Wi-Fi t-stat
Small retail store (1576)	3	Sanford	FL	Wi-Fi t-stat
Small retail store (1746)	3	Ocoee	FL	Wi-Fi t-stat

The demonstration sites were selected from a larger list of commercial office, restaurant, and small retail store locations, based on the following criteria.:

1. **RTU Coordination opportunity** -- Candidate sites were limited to those with 3 or more RTUs in total, with at least 2 of those units supplying a common space.
2. **Climate** -- Preference was given to sites with longer cooling seasons (e.g.: those in southern and western states).
3. **Range of disturbance scenarios** -- It is felt that offices would offer lower unmeasured disturbances, while fast food restaurants would offer higher disturbances due to food preparation and high customer turnover.
4. **Willingness to participate** -- The demonstration period required candidate sites to be made available on short notice for installation and model training. Participants were not charged for hardware, labor, nor any other associated services.

4.2. Approach to evaluate RTU Coordinator performance

To better assess performance improvements arising from the implementation of RTU Coordination, the algorithm is engaged on a “one day on, one day off” schedule. Thus, coordination is enabled every other day at each site so the normal performance may be compared with coordinated performance.

At each site, network-connected thermostats are used to control the units. On days when Unit Coordination is disabled, these thermostats default to conventional operation. On days when coordination is enabled, all thermostats are enslaved to the RTU Coordinator.

4.3. Deployment approach and status

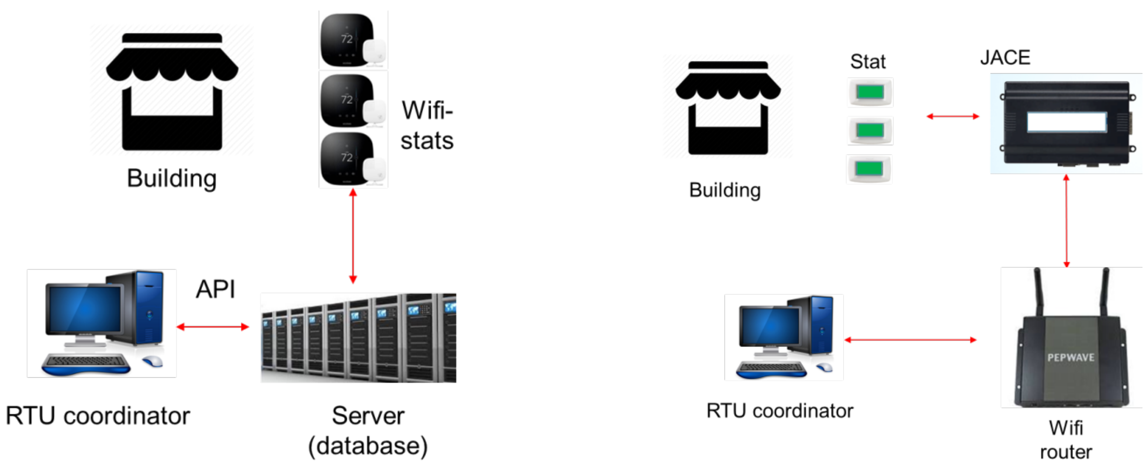

Figure 7: Control architectures used to implement the RTU coordinator with Wi-Fi-enabled thermostats (left) and JACE (right)

For scalable deployment of the RTU Coordinator, two control architectures were identified.

One approach (Fig. 7; left) uses web-enabled thermostats that communicate with the RTU Coordinator through a database. Ecobee3 was chosen for this implementation; it allows reading thermostat temperatures and RTU run times over a 5-minute interval. Thermostat set-points can be changed remotely.

The other approach (Fig. 7; right) uses a JACE (Java Application Control Engine) paired with a cellular router as a communications conduit between the RTU Coordinator and our test site thermostats. Despite the hardware differences, a single RTU coordination algorithm is used for control for both architectures.

A prototype commercial product based on the RTU Coordinator, PMUC (Performance Monitor /

Unit Coordinator), is being used for testing. PMUC runs on a standard Linux server located at FDSI's data center. This one PMUC computer can control multiple sites; in fact, it now serves all of the demo sites listed in Table 5.

JACE sites

At JACE sites, Honeywell T7350H thermostats (see Fig. 8) and Honeywell TR-21 remote temp. sensors control the RTUs. All t-stats are connected to a Vykon JACE JEC334 (see Fig. 9) via Lonworks network card; the JACE communicates with the RTU Coordinator (using BACnet/IP) over a private IP network (T-Mobile and Wyless) via a Pepwave MAX-BR1 cellular router installed at the site.

Figure 8: Typical Honeywell based thermostat installation at JACE sites (remote temperature sensors are employed to obtain measurements in the controlled spaces)

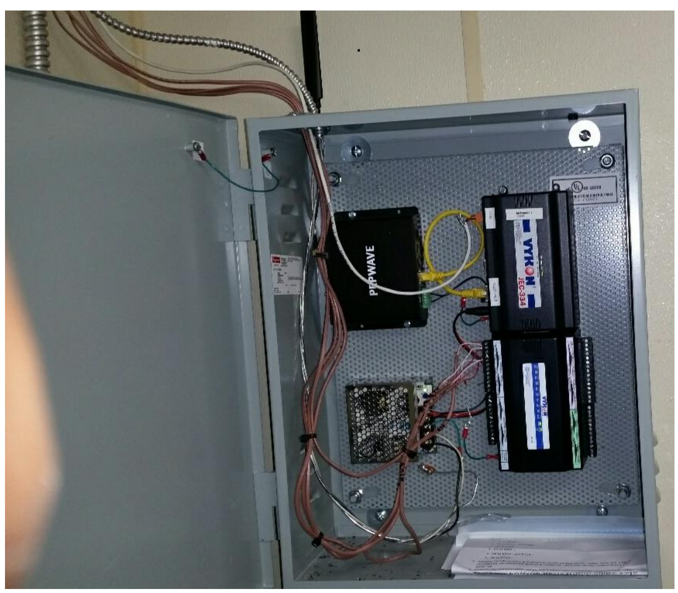

Figure 9: JACE Panel with Pepwave Wi-Fi router at upper left

The JACE sees the RTU Coordinator as a single BACnet device called ‘PMUC’. Each thermostat provides a set of readable points through which all necessary values are communicated from the site to the RTU Coordinator.

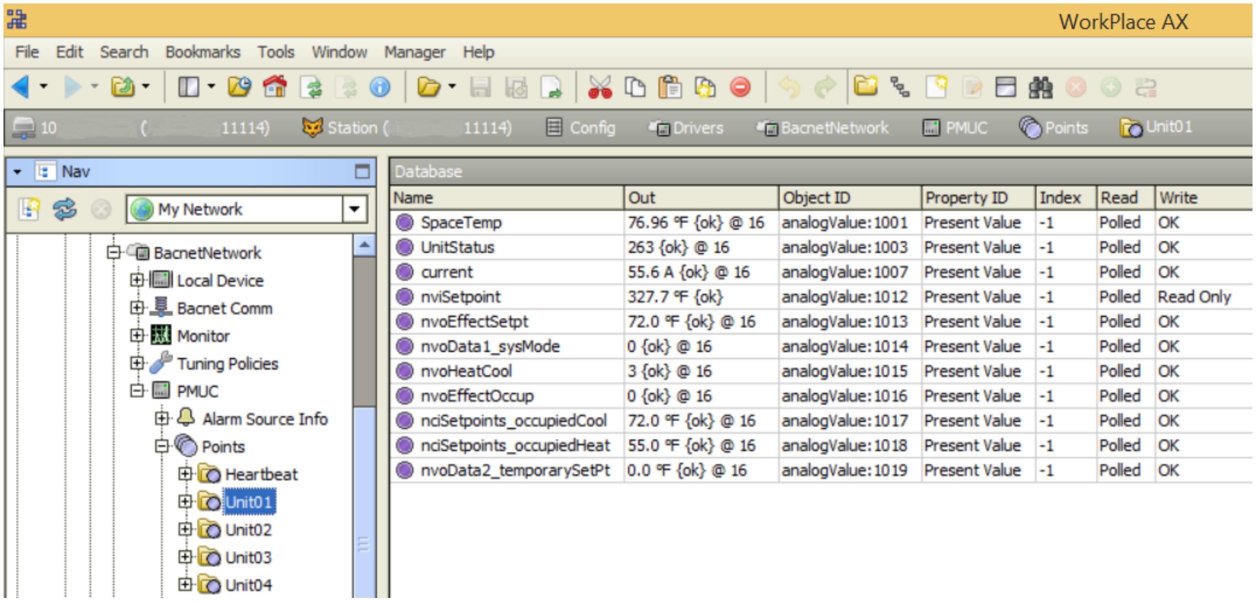

Figure 10: RTU Coordinator PMUC device shown in Tridium’s Niagara Workplace AX

AC power is monitored with a Mamac CU-855 or CU-865 self-powered current transducer (‘CT’) clipped onto one leg of the RTU’s three-phase input; at many sites, these CTs are located inside the electrical breaker panel (Fig. 11). From these current measurements and the nominal line voltage, we may calculate each unit’s energy usage.

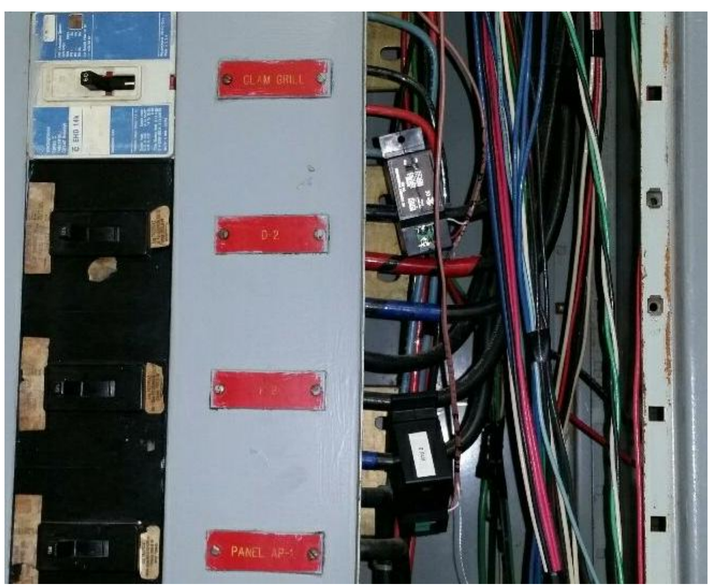

Figure 11: Typical electrical panel with current transducers installed

Wi-Fi-stat (Ecobee3) sites

Figure 12: Ecobee3 Wi-Fi thermostat

At Wi-Fi-stat sites, we control each RTU via a dedicated ecobee3 thermostat (see Fig. 12) paired with a wireless remote sensor. Using a Pepwave MAX-BR1 cellular router installed at the site, the t-stats upload their data to a server at ecobee, from which the RTU Coordinator server ('PMUC') can retrieve these data via ecobee's Application Program Interface ('API)'.

Overview of implementation approach for RTU Coordinator

In place of a conventional thermostatic controller, the Unit Coordinator implementation substitutes a multi-zone thermostatic algorithm run on the PMUC server. This server, which can control multiple client sites and their associated HVAC units, is currently located at FDSI.

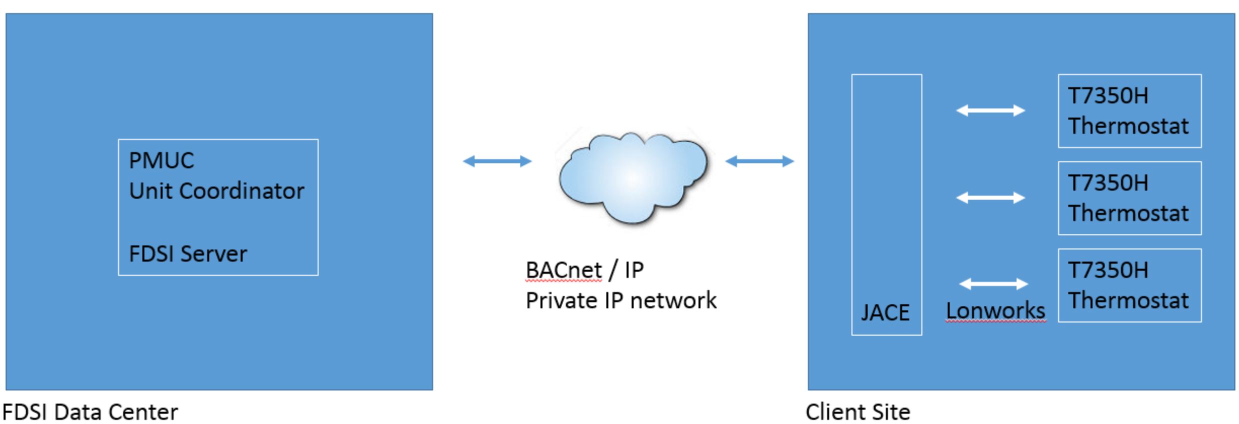

Figure 13: High Level Implementation Diagram

Server software implementation - RTU coordinator + communication

PMUC's server architecture involves several processes that run in individual Docker containers, communicating across containers via messaging, and storing/retrieving information in a database ('DB'). Docker encapsulation brings multiple benefits, including improved stability (if one process crashes, it won't crash the entire application), portability (moving the application between servers) and scalability across multiple sites.

All messaging functions are handled via Celery, a Python-based asynchronous task queue, with RabbitMQ as the message broker; i.e.: RabbitMQ alerts containers that new data are available. Celery also functions as our scheduler, triggering certain tasks to run regularly. The messaging architecture allows all processes to run asynchronously; if one process runs longer than expected, it will not impede any other process in the flow.

Configuration info (sites, units, thermostats, etc.) and calculated results are held in a Postgres DB, for sharing data between processes, and as the data-source for the User Interface ('UI'). Both Postgres and RabbitMQ are run in their own Docker containers.

The flow of data for the JACE implementation (see Fig. 14) can be described as:

1. The JACE sends values to the *BACpypes* (a Python library for BACnet communications) application, which then stores the data in a Postgres database.
2. In a separate container (‘poller’), the scheduled *Poller* process reads the latest cooling set-point ('CLMC') and space temperature ('SPTV') from the JACE.
3. If new data is available, ‘input ready’ message is sent to the unit-coordination algorithm. This algorithm runs in the *unitcontroller* container.
4. The unit-coordination algorithm uses *SpaceTemp* and *CoolingSetpoint* data to calculate new staging commands.
5. New staging commands are written to the DB and ‘output_ready’ message is sent to the output container, indicating new calculated data is available for processing.
6. As necessary, the *Output* process propagates all calculated values to tables (e.g.: tables for the UI; trending tables for algorithmic analysis).
7. Completing the flow, the *BACpypes* application writes each newly-obtained staging command to the JACE.

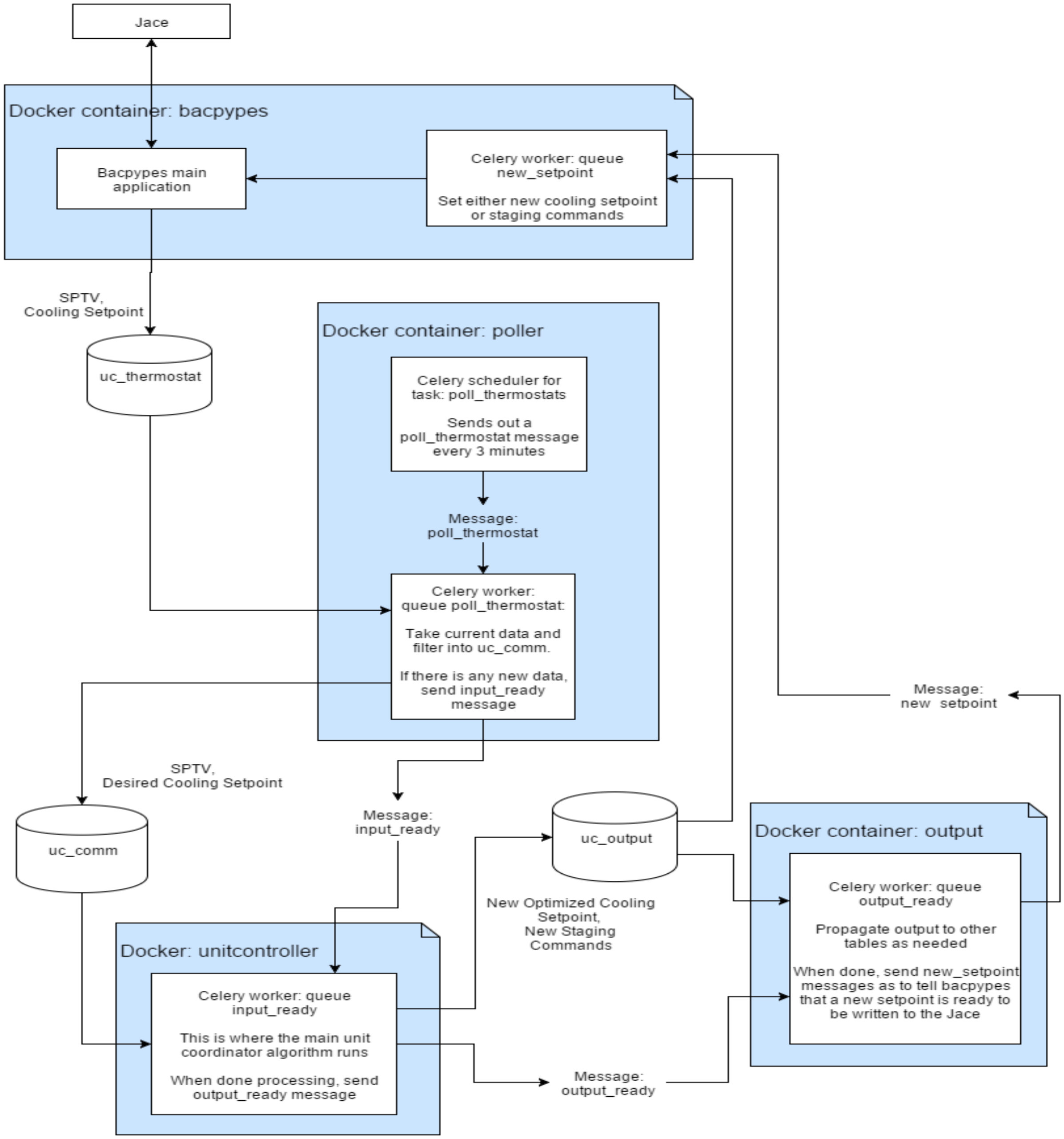

Figure 14: RTU Coordinator Architecture Diagram for JACE Implementation

4.4. Sample results for a small retail store

A sample comparison of results for a small retail store (site ID 0113) participating in our experiment is shown in Fig. 15.

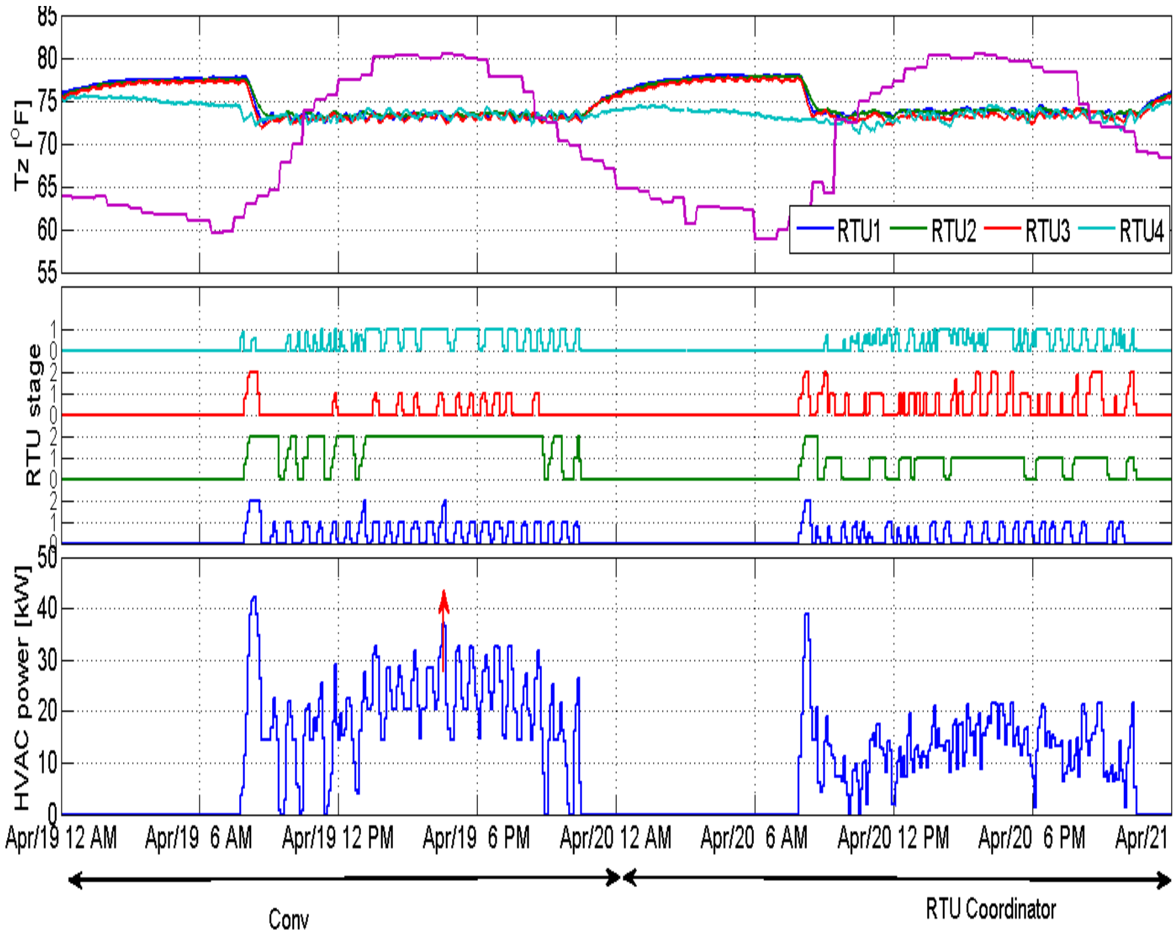

Figure 15 : Sample results comparison, conventional logic vs. RTU Coordinator (field evaluation)

The control strategy was toggled from conventional thermostat control (04/19/2016, Tuesday) to the PnP RTU coordinator (04/20/2016, Wednesday).

The site has 4 RTUs where RTU1, RTU2 and RTU3 are 2-stage units of 17, 15 and 8-tons, respectively, and RTU4 is a 5-ton single stage unit. Fig. 15 shows responses of thermostat temperature, RTU staging and total HVAC power for the site associated with conventional control and the plug-and-play ('PnP') RTU coordinator for two different days with similar ambient conditions (purple line).

As shown in the diagram, both controllers indicate that the highest electric demand during this test period occurred from 8:00 to 9:00 AM. This is due to abrupt set-point changes for all thermostats as corroborated by the temperature plot. This problem can be easily solved in the future via the addition of a simple low pass filter (e.g. a moving average filter) on the set-point signals for both controllers.

For both controllers, temperatures were regulated at around 73^o. We see that at 4:00PM under conventional control, RTUs 1, 2, and 4 were all operating at maximum stage, resulting in a high peak demand. But under RTU coordinator, all units do not operate simultaneously -- compare stages of RTUs 1 & 3, in particular. This represents a spot reduction in peak electricity demand of approx. ~50% , dropping from ~40kW to ~20 kW.

A summary of daily results for conventional and coordinator controls for energy consumption and peak electricity demand is shown in Table 6 for this site. From this, energy savings were estimated by comparing the averages of daily energy consumptions for the two controllers; the same calculation was applied to demand savings. The corresponding energy and demand savings for the small retail store building (0113) were 17.6 % and 12.9%, respectively, for this period.

Table 6. Comparison of a small retail store's daily energy consumption and peak electricity demand, contrasting the conventional ('Conv') and RTU Coordinator ('PnP') approach

Date	Control Approach	Average outdoor temp. [^{o}F]	Daily cooling energy [kWh]	Daily peak demand [kW]
2016-04-12	Conv	73.30	305.08	111.30
2016-04-13	Conv	72.52	315.18	104.98
2016-04-16	PnP	70.83	134.40	71.33
2016-04-17	Conv	66.80	192.39	103.50
2016-04-18	PnP	67.95	275.10	114.83
2016-04-19	Conv	68.45	289.65	110.23
2016-04-20	PnP	69.16	214.65	97.50
2016-04-21	Conv	72.53	293.75	112.00
2016-04-23	Conv	73.00	351.69	133.50
2016-04-24	PnP	73.00	348.31	116.65
2016-04-25	Conv	75.00	318.05	128.48

5. CONCLUSIONS

A practical multiple RTU coordination algorithm was developed and evaluated in terms energy and demand savings, both in simulation and real-world testing. Using recorded data from an EMS, simulation tests were carried out for BoA sites to gain an understanding of the overall market potential. Based on these evaluations, typical cooling season energy and peak demand savings are expected to be about 15%. These results are consistent with savings previously determined for the Unit Coordinator at demonstration tests. The 10 most promising BoA sites have economic paybacks of less than 2 years. In addition to the performance evaluation, two control architectures for scalable deployment of the RTU coordinator were developed and implemented for application to small/medium sized buildings.

As noted earlier, an original plan for demonstrations at 10 Bank of America sites was abandoned due to security concerns and a change in personnel involved in the facility management. Over a three-month period, our plan was changed drastically, with remediation achieved by engaging new customers through FDSI. Although the change to alternative demonstration sites moved quickly, this presented the following technical challenges:

- A new strategy for deploying the RTU Coordinator had to be developed and tested; the original control architecture reported in milestone 2.1c was counting on data from the EMS system employed at BoA sites.
- Lack of existing EMSs at these sites meant sourcing and installing more hardware at each site (e.g., a Web-enabled thermostats and JACEs) to implement the remote RTU Coordinator.
- Due to unseasonably cool weather (and/or low cooling loads at specific sites) so far this year, opportunities for full-day Unit Coordination have been limited.

Despite these challenges, the RTU coordination algorithm is currently running at the 10 demonstration sites will soon be running at an additional 4 sites. However, data available for full assessment is limited. The algorithm will run for the entire cooling season and the overall assessment will be updated as new results become available.