# FOURTH AND FINAL REPORT EAA PROJECT 2.D: END-USE METERING LOAD RESEARCH

## Masdar Institute

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# **EXECUTIVE SUMMARY**

The technical potential for a given energy efficiency measure is the product of baseline end-use energy and percent savings. There are uncertainties associated with both terms however the uncertainty in baseline energy end-use is usually the larger of the two uncertainties. Indeed post-retrofit end-use energy estimates often form the basis of savings estimates in which case estimated savings may be more than first-order sensitive to baseline errors. There are many ways to estimate end-use intensities (EUIs) for a given building (GPC14 2000) of which end-use metering is the most accurate. For program design, one needs EUI estimates for a population of buildings, preferably keyed to building characteristics such as type, size, and age. In high performance buildings cooling load is dominated by the internal gains of all electrical and-uses except for exterior lighting and chiller plant. The exceptions comprise loads whose energy is dissipated outdoors while all the other loads contribute directly and to cooling load. Therefore it is important, for CCP program design and evaluation, to understand how electricity is used within UAE buildings. Measurement and verification of savings resulting from building envelope and cooling equipment interventions, as well as measures targeting other end uses, is best accomplished by continuous measurement of the loads in question such that pre-intervention and post-intervention load models can be developed that account for occupant schedules (daily, weekly), sun position, weather, and other external conditions.

In the first two quarters, technologies of end-use metering were reviewed and a specification was developed for the next generation end-use meter/logger. Requests for building stock data were made to ADWEA and RTI. These data facilitated selection of a stratified sample for end-use metering.

In the third and fourth quarters, initial load-research logger and sensor designs were completed and prototypes were built and tested. In addition to general functionality, test results indicate current measurement accuracy of 0.3% between 20 and 100% of full scale over a range of signals. Based on the RTI survey results of 996 commercial and 203 residential buildings (villas) a preliminary stratified sampling plan was developed.

In the fifth and sixth quarters the wireless load sensor (current transducer-CT) design reached an impasse with respect to its ability to perform its monitoring and communications tasks while being self-powered, especially when applied to low power circuits. A decision was made to abandon wire-less and use instead the most recent low-power wireless technology (Bluetooth Low Energy) such that battery power is feasible. Testing of the new CT prototypes indicate that waveform and synchronization of the previous design can be achieved and that one year battery life is possible with 10s sampling of very branch circuit. Further tests of synchronization accuracy and jitter (both improved) are presented in this report. Communication functions (waveform transmission, acknowledgement and clock correction) have also been successfully tested.

Twenty buildings (including 9 ADCP) were selected for monitoring and two site visits were made in order to document main distribution circuits, existing tenant metering, and branch circuits of common areas, tenant spaces, and water, cooling distribution, chiller and ventilation air conditioning systems.

In the latest reporting period (sixth through ninth quarters), design of the battery-powered wireless CT and logger was completed to satisfy the initial requirements. Following laboratory tests, production for both devices was initiated. Metering equipment was installed in a typical A/C panel. Cooling energy use is reported for the first summer month of monitoring.

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## **1** INTRODUCTION

The technical potential for a given energy efficiency measure is the product of baseline energy enduse and percent savings. There are uncertainties associated with both terms however the uncertainty in baseline energy end-use is usually the larger of the two uncertainties. There are many ways to estimate end-use intensities (EUIs) for a given building (GPC14 2000) of which end-use metering is the most accurate.

Many end-use metering projects were conducted in support of U.S. utility DSM programs in 1980-1995 time frame, e.g. Hood River (ENB 1989) and ELCAP (ENB 1992). These projects installed specialized end-use metering equipment in a large (~400) number of detached residential buildings and, in the case of ELCAP, about 100 commercial buildings. In the latter project a stratified sample was developed from regional building stock data. EUI estimates and load profiles were obtained based on 15-minute data for one-year or longer records. The results were keyed to building characteristics such as type, size, and age. The ELCAP database is publicly now accessible (NWPPC 2013).

The ELCAP purpose-built end-use metering loggers served as a model for two commercial products introduced in 1990, widely used in subsequent decades, and still, in one case, on the market as of 2015 (Enernet). The C180 and K-20 load-research meters (LRM) were 16-channel loggers with about 1MB memory that could be interconnected (for multiples of 16 channels) and accessed by a single direct connection or telephone dial-up. Installation time was about one person-day per logger because a separate logger panel was required and wiring had to be run between the logger and the electrical distribution panel of interest. Although various new sub-metering products have been released nothing has come to market that will fit completely inside a distribution box, provide multi-channel true-power logging, and eliminate CT lead wires and associated installation labor.

With the foregoing background, a project to support planning and evaluation<sup>1</sup> efforts of EAA's Comprehensive Cooling Program (CCP) was organized around the following tasks:

- 1. Develop sampling plan based on RTI building-stock data base and other relevant sources.
- 2. Design and test prototype next-generation (NG) load research meter (LRM)
- 3. Recruit participants and deploy metering devices
- 4. Operate an end-use metering network to accrue load research data
- 5. Perform end-use analyses.

<sup>&</sup>lt;sup>1</sup> Savings measurement and verification (M&V) is one of the main activities of such evaluation efforts.

# 2 METERING PLAN

One of the main barriers to significant advancements in plant (HVAC, central plant and CHP) controls, continuous commissioning, and fault-detection is the high cost of reliable power sensor systems. To obtain a realistic understanding of building loads, the typical diurnal and seasonal profiles of real and reactive power use by HVAC motors, package and split A/C, chillers, water heaters, lighting transformers, lighting systems, and other important end-use equipment must be measured. These data support commissioning, whole-building and zone-level fault detection and diagnosis (lights left on; simultaneous heating and cooling), chiller plant controls (VSD pump, fan and chiller power trade-offs), tenant sub-metering, occupancy control, and controls for demand response.

Task 1 efforts resulted in a standardized metering plan template for mixed use high-rise buildings and a sampling plan to be applied to participating CCP buildings. Details of these efforts, presented in the 3<sup>rd</sup> progress report, are summarized below.

Figure 1 shows a typical one-line schematic of building power distribution. In the schematic each line represents a 3-phase circuit as shown, until the final metering or distribution box from which some loads are 3-phase other loads (the majority) are single phase. A typical building of this type is expected to require from 300 to 1500 CT's, depending on the number of floors sampled and total number of circuits per floor.

A typical tenant distribution board is shown in Figure 8 and its circuits are documented by a printed table, required by building code, displayed inside the panel access door as shown in Figure 9.

Due to the large numbers of end-use circuits and the difficulty in scheduling entry to individual units (both residential apartments and commercial suites), it is essential to make the installation visits as short and unobtrusive as possible. The development of wireless snap-on CT's and wireless loggers to enable monthly downloads from outside the units is motivated by this requirement.

Installation of large numbers of CTs is desirable for end uses in which there is large diversity such as lighting and plug loads. The end-use load history recorded by a single current transducer is useful, of course, but it gives no idea of the end-use intensity, i.e. ratio of aggregate load (of the end-use in question) to GFA for a given building. Reliable estimates of average EUI, of average daily, weekly, and seasonal EUI profiles, and of their variances can only be obtained by statistical analysis of large samples. In very large buildings with relatively homogeneous use one may obtain sufficient information about the population of a given end-use by sampling, say, as few as 50 of 1000 circuits (5%). However, because statistical adequacy of a sample size can only be determined by *a posteriori* analysis, it is advisable in planning to pick conservatively large sample sizes for each end use.

In contrast, the daily, weekly and seasonal history of a chiller plant may require only two (3-wire) or three (4-wire) CT's when the plant is powered by a single 3-phase circuit. However in buildings with multiple chillers, DX, or multi-split units dedicated to different zones, we must expect some level of diversity. In these cases it is desirable to monitor at least half of the connected load of primary cooling equipment. Once again, because statistical adequacy of a sample can only be determined *a posteriori*, the prudent course is to pick conservatively large samples of A/C units.







Figure 2-Circuit Breaker Panel inside a Commercial Office

RATING RATE.		DB.RE	DB-TO4 SMDB-T 24						40A TP ISOLATOR				
OF	OF RCCB	DB LO OFFK	CATION : BLOCK-B	DB TYF 8 WAY	PE : TP&N M	ACB(4+4	4WAY)	MAIN 5x1	NCOMING C			ONDUN	rs
		CCT			WIRE	мсв	LOAD/	NO OF	TOTAL LOAD	L	OAD IN I	ĸw	DEMONIS
		NO.	LOAD DESCRIPTI	NC	SIZE (mm2)	(AMPS)	(IN KW)	FITTING	(IN KW)	R	Y	B	REMARKS
		R1	LIGHTS-OFFICE(L1-L14) + L8A,L4	A	2.5	10	0.1	16	1.6	1.6			
		Y1	FCU-1 (TF-3)		4	20	1	1	1		1		
	FCU	B1	LIGHT BATH(L16-L17)		2.5	10	0.1	2	0.2			0.2	
	+ 4	R2	LIGHTS-OFFICE(L18-L30)		2.5	10	0.1	13	1.3	1.3			
	LIG	Y2	SPARE			10					1		
	Dma	82	SPARE			10						1	
	8 10 AY 1	R3	SPARE			10			1997 30	100.0			
	AW 4W	¥3	SPARE	a set the set		10						6.63	
	A	83	SPARE			10						12.00	
TOR	40	R4	SPACE			-							
OLA		¥4	SPACE										A. S. S. S. S.
15		84	SPACE										
0 TP	POWER	R5	20A DP SWITCH POWER	SOCKET	4	20	1.0	1	1.0	1.0			12.3
		¥5	SOCKETS RING(S15-S20	1)	4	32	0.2	6	1.2		1.2		
-		B5	SOCKETS RING(S7-S14)		4	32	0.2	8	1.6			1.6	
		R6	SPARE			20							
	Am	Ye	SOCKETS RING(S21-S2	5)	4	32	0.2	6	1.2		1.2		
	B 30	B6	SOCKETS PANTRY S27,S27a,S28,S28a)RING	3	4	20	0.2	4	0.8			0.8	
	RCC	R7	SPARE			20	-		•	•			
	ISA	¥7	SOCKET OUTLET FOR	EL.JB.		20		1					
	14	87	WATER HEATER		4	20	1.5	1	1.5			1.5	
		Ra	SPARE			20			•				
		Y	SOCKETS RING(S1-S6)		4	32	0.2	6	1.2		1.2		
		88	LIGHT PANTRY(L15)	1800.50	2.5	10	0.1	1	0.1	1		0.1	
			TOTAL LOAD =	12.7 KW					12.7	3.9	4.6	4.2	REV:3

Figure 3- Panel documentation of DB Circuits of Figure 2

In summary, the daily, weekly and seasonal profiles needed to understand baseline loads by end use. With a statistically valid baseline can one more effectively design programs to improve and maintain energy efficiency in new and existing buildings.

A multi-building metering plan developed in the 3<sup>rd</sup> reporting period based on CCP survey data (summarized in Appendix B) is reproduced in Appendix C.

# **3 END-USE METERING SYSTEM**

Task 2 of the project was development of an advanced low-cost power monitoring system comprising wireless current transducer (CT) and a logger that communicates with up to 64 CTs. We refer to this system as the new load-research meter (new LRM) to distinguish it from the old ELCAP LRM system. The goal has been to significantly reduce the cost of the multi-channel concentrator device (one per panel) and drastically simplify the installation of multiple (up to 64 per panel) current transducers. In this section we describe the new LRM and present final design revisions and test results. Previous designs and test results were described in progress reports of the 2<sup>nd</sup> and 3<sup>rd</sup> reporting periods.

## 3.1 Logger Description

Figure 4 presents a size comparison, in 1:1 scale, of the ELCAP LRM logger (Enernet K20) and the new LRM logger. A one Dirham (24 mm) coin was placed on top of the case of the new LRM for size reference.



Figure 4- Size comparison between ELCAP logger<sup>2</sup> and the new wireless logger (Scale 1:1)

Figure 5 shows a typical ELCAP logger installation. Leadwires (black and white twisted pair) have to pass outside the DB and into the adjacent logger panel, in this case a C180. Figure 6 shows a typical wireless logger installation using the initial prototype. Its compact form allows the wireless logger to be mounted inside distribution panel, eliminating the need for a separate box and external cables between it and the panel. Each of 18 wireless CTs can be identified by the H pattern on top of its hinged clasp. The clasp closes the CT's ferrite core about the conductor being monitored.

<sup>&</sup>lt;sup>2</sup> <u>http://enernetcorp.com/k20-power-measurement-and-recorder/</u>



Figure 5-Traditional externally mounted logger (left); hardwired CTs installed in target panel (right).



Figure 6- Panel mounting of concentrator (Revision A) and CTs

An internal view of the wireless logger, revision C, is presented in Figure 7.

Figure 8 shows the locations of modules inside the concentrator, including:

- On-board power supply, requiring no external power adaptor
- 4 isolated analog channels (A-B-C Phase and Neutral)
- 0.1% Accuracy Analog-to-digital converter reference source
- High performance processor from TI at 80MHz
- Separate oscillator for the main processor and the Real time clock
- Over 1 year of data logging capacity using standard microSD memory card
- Backup battery for (**RTC**) Real-Time Clock
- Bluetooth Low Energy for communication with the sensors
- Bluetooth V2.0+EDR for communication and download of data



Figure 7- Internal view of the concentrator revision C



Figure 8- Concentrator's internal modules

## 3.2 CT Description

The wireless snap-on CT hardware has been progressively optimized in functionality, cost, reliability and safety. The current version uses a

Given the potentially noisy environment of the distribution panel, a series of protection methods for the circuit are implemented. The initial protection stage comprises a Zener diode bridge embedded in the CT terminals limiting the voltage reaching the main control board in the event of open burden resistor. The second stage protects the circuitry from ESD with low clamping voltage. In order to protect the Analog-to-Digital converter, a voltage clamping circuit using Schottky diodes is also used, limiting the input signal from -0.3V to Vcc+0.3V. The circuit also implements a low-pass RC filter.

Figure 9 presents the board layout for Revision C of the CT board, measuring 20.5mm x 25mm, under production during the time of this report submission. Figure 10 presents Revision B of the CT printed circuit board with all components mounted. Figure 11 shows four of the completed wireless CTs. A corner of its battery clip is visible in the top left CT.



Figure 9- CT Board layout Revision C



Figure 10- CT Board assembled Revision B

The main features of the CT are:

- FCC certified Bluetooth Low Energy (BLE) radio
- ESD/Spike protection
- Differential analog-to-digital converter
- Over-voltage protection for both positive and negative sides for both channels
- Ultra-low energy consumption TI SoC (System on Chip)
- Estimated over 1 year battery lifetime
- Four different full-scale load configurations (12, 20, 50 and 60A)
- Sufficient capacity for small panel feeds (60A)
- Compact design
- Low cost



Figure 11- Four Rev-B CTs fitted with prototype acrylic board covers

## 3.3 Beacon Synchronization Jitter

Synchronization iitter is defined as the variability of time elapsed from concentrator's sending the beacon signal to when the CT (having received and processed it) starts a sampling sequence.

In order to test Synchronization Jitter, an output port in the concentrator was configured to generate a low-level signal before starting the sampling sequence of the voltage waveforms, while the CT sets an output port high before starting the sampling sequence of the current waveform. By measuring the variation between the two edges, it is possible to estimate the Synchronization Jitter of the system.

The test was performed on the Tektronix TDS 2024B Oscilloscope, by connecting the output port of the concentrator to the Channel 1 input of the oscilloscope, while the output port of the CT was connected to the Channel 2 of the oscilloscope.

A total of 20 sequences consisting of:

In the concentrator:

- sending the Synchronization beacon;
- counting a Synchronization delay;
- configuring the sampling sequence for the voltage waveforms;
- setting the output port low;
- starting the sampling sequence;
- delay until next sampling sequence;

In the CT:

- waking-up from a low power state;
- receiving the Synchronization beacon;
- processing the Synchronization beacon;
- setting the output port high;
- starting the sampling sequence;
- enter low power state;

By using the Channel 1 as the triggering channel, Figure 12 shows the obtained results from the test.



Figure 12- Beacon Synchronization Test result

It can be observed that the start of the sampling sequence on the CT varies from the start of the sampling sequence in the concentrator. By this test the variation was quantified.

Based on the results shown in Figure 12, the sampling sequences in the CT delayed from -1.6 $\mu$ s to +2.2 $\mu$ s.

Given the period of a 50Hz system waveform, the sampling sequence delay variation ranges from - 0.008% to +0.011%.

A second test with 150 beacon sequences was conducted to assess the Synchronization Jitter over a longer period of time, using an interval of 10 seconds between beacons. Figure 13 presents the results for the test where a variation of  $3.52\mu$ s, equivalent to a shift of  $0.063^{\circ}$ , was observed. This is a considerable improvement (over the already good results) presented in the report relative to the  $4^{th}$  quarter. Overall the jitter was reduced from 15.6 $\mu$ s to 3.52 $\mu$ s.



Figure 13- Long duration Jitter test

## 3.4 Burden Resistor

In a typical residential/ or commercial DB, different circuits in a distribution panel have different capacities. In order to allow a higher resolution in the current measurements by utilizing the full range of the Analog-to-digital converter, each CT would require its burden resistor to be dimensioned based on the maximum capacity of the circuit it is being installed on, creating a broad range of CTs configuration.

The full-scale current sampling configurations and the burden resistors were based on the results from the field surveys presented in the progress report of the 3<sup>rd</sup> reporting period. On a typical low-voltage distribution panel for a residential/commercial unit, as depicted in Figure 2 and Figure 3, five different ratings were encountered. Table 1 summarizes the number of circuits and the rated capacity for the two panels analyzed.

Rated Current (A)	Quantity	% of total
10	11	30
16	2	6
20	12	33
32	10	28
40	1	3

Table 1- Summary	of the	number of	circuits	based	on rated	capacity
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By manufacturing and stocking boards assembled with the variety (at least 3) of different burden resistors required, the number of each board manufactured would be reduced, directly increasing the cost per board, and the final cost of the unit. The solution adopted has a series of burden resistors pre-assemble on the CT board, with four configurations based on jumper connections. By having a configurable design, different CTs can have a different full sampling range, using the same circuit board, therefore reducing production costs and covering a large number of circuits with the full sampling range of the Analog-to-digital converter.

Figure 14 presents the schematic of the burden resistor configuration and the jumpers in place.



Figure 14- Schematic of burden resistors configuration circuit

The jumper configuration is made using solder to bridge adjacent pads as shown in Figure 15, making a quick and cheap process for configuration. Table 2 presents the four different jumper configurations, the equivalent burden resistor value and the current in Amps that produces a 1V RMS signal in the input of the Analog-to-Digital Converter (full range). Figure 16 presents the variation on Secondary voltage given different burden resistors. As the response of different CTs vary and values of resistor are approximate to 0.5%, a calibration routine can be performed in each CT to account for the production variations.



Figure 15- Configuration of burden resistors. Either or both jumper pad pairs can be easily bridged during assembly.

Table 2- Jur	nper configuration	and equivalent	burden resistor,	/ full range current
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J1	J2	Ohm	Current for 1v RMS
0	0	250	12.4
0	1	150	20.7
1	0	60.6	51.6
1	1	52.2	59.6







V in Volts AC RMS I in Amps AC RMS R in Ohms



Figure 16- Electrical output of the CT given different burden resistors

## 4 WAVEFORM SAMPLE ANALYSIS

### 4.1 Voltage sample

A series of tests were conducted over each board revision in order to certify design changes and accuracy of the final system. A 127VAC high precision signal generator for the calibration of the concentrator was used and its accuracy assessed. Figure 17 presents the raw sampled voltage data where the same signal was injected in all four inputs from the signal generator. Given the variation between components used for each channel, a slight variation is visible between the channels (Channel A being the most affected in this case). After this assessment, a gain correction and DC correction was obtained and inserted in the concentrator's firmware for automatic correction of the sampled data for each independent channel. A first order Fourier series (Eq. 1) was fitted to the raw sample data with the result presented in Figure 18.



Figure 17- Raw sampled data from voltage source



Figure 18- (a) 1st order Fourier curve fitting, (b) Fit residuals

f(x) = a0 + a1 \* cos(x \* w) + b1 \* sin(x \* w) Eq. 1

Coefficients (with 95% confidence bounds):

- a0 = 2161 (2161, 2162)
- a1 = -72.36 (-73.77, -70.95)
- b1 = -932.7 (-933.5, -931.9)
- w = 0.02455 (0.02454, 0.02456)

Goodness of fit:

SSE: 4215

R-square: 1

Adjusted R-square: 1

RMSE: 4.09

The RMSE is 0.44% of  $(a1^2 + b1^2)^{0.5}$ .

Figure 19 presents the curve fitting for the sampled voltage directly from the grid (237Vrms), after being adjusted for DC and scaled. It can be observed that a higher distortion occurs in the peaks (higher residual module), as well as some harminic distortions.



Figure 19- (a) 1st order Fourier curve fitting, (b) Fit residuals

Coefficients (with 95% confidence bounds):

a0 = -0.161 (-0.6894, 0.3674)

a1 = 39.06 (37.58, 40.53)

b1 = 335.4 (334.6, 336.2)

w = 0.02459 (0.02456, 0.02462)

Goodness of fit:

SSE: 4598

R-square: 0.9997

Adjusted R-square: 0.9997

RMSE: 4.271

## 4.2 Voltage and Current sample

Using a reference current source equipment for producing 0.1% sinusoidal line-frequency current (Figure 20), the system was simulated with one CT. Figure 21 presents the RMS voltage and current, while apparent power and power factor during the sampling period is shown in Figure 22.



Figure 20- Model 935A Current Source<sup>3</sup>

<sup>&</sup>lt;sup>3</sup> http://www.arbiter.com/images/catalog/935A front large ps.jpg



Figure 21- RMS Voltage and Current during sampling



Figure 22- Apparent Power and Power Factor during sampling

Figure 23 presents the plot of a captured waveforms for Voltage and Current. It is possible to discern some artifacts mainly in the voltage waveform due to noise and harmonic distortions that were not present during the calibration with the voltage signal generator. Figure 24 presents the apparent power sampled by the system.



Figure 23- Plot of sampled Current and Voltage



Figure 24- Plot of Apparent power

Using the Matlab for processing the collected data, the RMS Voltage of the waveform is 241.2V, while the RMS Current equals 34.7A. The average apparent power for the sampled waveforms is 8,360VA, referent to an error of 0.529% compared to the value measured by the Arbiter system.

## 5 END-USE METERING RESULTS

For the first end-use metering installation a control building at the beam-down optical experiment (BDOE) was selected. This building has a dedicated distribution panel for air conditioning equipment. The A/C equipment comprises two 10-ton outdoor units and eight indoor units each powered on separate circuits. The hourly loads of outdoor units are shown in Figures 25 and 26.

Here the loads of two identical multi-split units, one serving the east end and the other serving the west end of a one-story office/lab building, are plotted showing only small effects of cooling load diversity. The main difference is that the east unit ramps up earlier (effect of morning sun on east wall) while the west unit ramps down later (effect of afternoon sun on west wall).





## 6 CONCLUSIONS

The technical potential for a given energy efficiency measure is the product of baseline end-use energy and percent savings. There are uncertainties associated with both terms however the uncertainty in baseline energy end-use is usually the larger of the two uncertainties. When post-retrofit end-use energy estimates form the basis of savings estimates, as is often the case, estimated savings may be even more than first-order sensitive to baseline errors.

Of the many ways to estimate end-use intensities (EUIs) for a given building (GPC14 2000), end-use metering is the most accurate. For program design, one needs EUI estimates for a population of buildings, preferably keyed to building characteristics such as type, size, and age. In high performance buildings the cooling load is dominated by the internal gains of all interior end-uses. For effective CCP program design it is therefore crucial to understand not only the cooling plant loads (EUI, seasonal and daily variations) but how all of the electricity end-uses stack up within UAE buildings.

Historically, the high cost of installing accurate end-use metering systems has severely limited acquisition of the data needed to reach this understanding. The main objective of this project has been to develop a cost-effective wireless end-use metering system that is accurate, reliable and easy to install.

To accomplish the goals of the project, technologies of end-use metering were first reviewed and a specification was developed for the next generation end-use meter/logger.

Initial load-research logger and sensor designs were completed and prototypes were built and tested. In addition to general functionality, test results indicated current measurement accuracy of 0.3% between 20 and 100% of full scale over a range of signals. Communication was implemented in the initial design via Wi-Fi (TCP-IP). As a result of the requirement for a micro-processor/SoC capable of supporting Wi-Fi and limited power harvesting capacity the prototype CT had a dropout current of about 1.5A.

However, the high drop-out It was necessary to abandon Wi-Fi and use instead a recently released low-power wireless standard (Bluetooth Low Energy) such that battery power (augmented, possibly, by power harvesting) is feasible. This required a change of MCU and ADC. Testing of the new CT prototypes indicate that waveform and synchronization of the previous design can be achieved and that one year battery life is possible with 10s sampling. Further tests of synchronization accuracy and jitter (both improved) are presented in this report. After testing of communication functions in the lab 16 pre-production units were assembled and installed, with v2 aggregator, in a typical A/C panel of an occupied building.

Based on the RTI survey results of 996 commercial and 203 residential buildings (villas) a preliminary stratified sampling plan was developed. Two ADCP buildings were surveyed to document distribution circuits, existing tenant metering, and branch circuits to common areas, tenant spaces, and water, cooling distribution, chiller and ventilation air conditioning systems.

The wireless metering equipment was installed in a typical A/C panel. Hourly energy use by each circuit is reported for the first summer month of end-use metering.

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## Appendix A: 64-Channel Next-Gen Load Monitoring System Spec

Although a large number of smart meter, panel circuit monitoring (Power Scout, Veris...for commercial buildings) and plug load monitoring systems (home energy feedback products) have emerged, because of limited market size nothing with complete load research functionality has emerged since ~1990. Meanwhile the existing load research loggers (C180, K20) have become progressively less attractive as their connectivity technologies (RS232, POTS) and PC interfaces (DOS, WIN3.2) have become obsolete. To fill the current need, a *next generation load research logger* specification was developed. Improvements in size, external connectivity (LAN, USB, wi-fi), increased number of channels, and micro-controller-based current transducer (CT) were specified. The advanced CT provides a path to future improvements such as higher accuracy (by on-chip CT-specific calibration factors), higher sampling rates, wireless connection, and load identification by power signatures.

The detailed specification developed for this project follows.

# 2013.03.05 EAA End-Use Metering Logger Specification Prototype and Initial Production

### **Component options:**

**3-component version**-*CT, PT, concentrator; concentrator may be in- or out-side the panel* Option 1: PT communicates with CTs, performs P,Q calcs, and sends result to concentrator at ~0.2Hz Option 2: PT communicates with CTs, performs P,Q calcs, and sends result only at logging interval. Option 3: PT sends time synch to CTs and concentrator; PT and CTs send waveforms to concentrator at ~0.2Hz; this option has potential for fewer PTs than panels.

**2-component version**-*PT*/concentrator combined; user-concentrator access by wi-fi only (Option 4) Specifications that follow are written for Option 3; adjust as appropriate for other options.

### System Accuracy:

Battery clock: 20 ppm 0~60°C during power outage Frequency: 0.1% (this only matters for micro-grid apps where line frequency may vary) For pure sine I,V RMS I,V  $\pm$ (0.3%rdg + 0.3%FS) P,Q  $\pm$ (0.5%rdg + 0.5%FS) I,V Waveforms  $\pm$ (0.5%rdg + 0.5%FS) P,Q harmonics 2..16  $\pm$ (1.0%fund + 0.5%FS) For I<sup>2</sup>C-connected 50A CT, starting current will be 25ma; for 200A CT it will be 100ma Exception: for self-powered CT starting current will be 100ma (see CT spec below)

### **Concentrator Description:**

Size, material, approvals: 1- max 10x15x3.5cm (10x20x3.5cm if concentrator and P are combined) 2-flame rated plastic UL-94-V0 3-max weight 300g 4-power 10-40V AC or DC 10ma max; or A-N powered 85-277VAC 5-FCC conducted and radiated EMI 6-UL for use inside 600V panel (classification: lab & instrumentation)

### Hardware Functions:

1-receive time synch accurate to 50us (based on 10 consecutive A-phase zero crossings) 2-receive A, B, C, N magnitude & waveform from wireless PT sensor

3-receive magnitude and waveform from each of 64 wireless CT

4-use "average" CT zero-crossing if PT fails

5-broadcast time-synch to all CTs at ~0.2Hz

6-prompt and receive unique id from PT sensor

7-prompt and receive unique id from each of 64 wireless CT

### Software Analysis:

1-compute RMS current and DFT for each CT

2-compute RMS voltage and DFT for each phase A, B, C, N

3-compute true power and 256-point waveform for each user-defined CT-voltage<sup>4</sup> association 4-compute VAR and PF for each user-defined CT-voltage association

**Configuration Protocol** 

1-set clock (if can't get from internet; clock basis (line default or RTC) selected by user)

2-select frequency of clock update (internet) and whether to update upon connection  $^{\rm 5}$  to user PC/PDA

3-set time-series logging rate  $\Delta t$ =1,2,3,4,5,6,10,15,20,30 minutes, or 1,2,3,4,6,8,12,24 hours 4-detect new device (CT, PT) mode

5-prompt user for name, phase, ckt type (single, delta, wye, L-L 1-phase, special<sup>6</sup>) and I-V association 6-perform 3-phase diagnostic, balanced or unbalanced

7-clear time-series memory

8-clear configuration memory except device id's

9-clear device id's

User Action Protocol (prompt for each)

1-most recent sample of RMS  $I_{j,}$  RMS  $V_{A,B,C,N}$  and user-defined  $\mathsf{P}_{i,}Q_{i}$ 

2-most recent waveforms list  $I_{j} \mbox{ and } V_{A,B,C,N}$ 

3-list  $I_j$  definitions

4-list I-V associations

5-download all time-series data recorded since previous download

6-download specified time range

7-download as far back as memory goes

8-check device id's (list time of last ACK for devices absent more than ddd.hh:mm:ss dflt=000.00:30:00

### **CT Description:**

Size, material, markings approvals:

1-type split core; note WxLxH where L is measured on conductor axis

2-for 1cm o.d. wire, 50A (75A max RMS): max size =2.5x3x5cm

3-for 1.9 cm o.d. wire, 200A (300A max RMS): max size = 5x6x3cm

4-material flame rated plastic UL-94-V0; CT to survive overload: T<sub>amb</sub>=90C amb., 150C pri. conductor 5-max weight

6-FCC conducted (via primary conductor) and radiated EMI

7-Source arrow white on black

Hardware Functions:

1-all functions self-powered down to 1400ma primary current

2-can respond "alive" (ACK) at 0.017Hz down to 600ma primary current

3-factory measured frequency response and non-linear scale factor burned in each CT

4-Unique ID burned in each CT

Comms/software Functions:

<sup>6</sup> E.g. main feed

 $<sup>^4</sup>$  Voltage difference, e.g A-B, B-C, C-A, A-N, B-N, C-N, N-Gnd; need separate  $V_{A,B,C,N}$  for 120/208 and 277/480

<sup>&</sup>lt;sup>5</sup> Prompt user to verify that PC/PDA time is correct to tolerance before updating

1-receive time beacon; send ACK after unique delay established during configuration
2-upon prompt return magnitude and scaled 256-byte waveform at whatever rate the power harvesting situation will support (0.2 Hz max)
3-other functions associated with previously enumerated concentrator functions
4-CT fallback—IC2 (daisy chain on zip-pair also supplies power)

### PT Description:

Size, material, markings, approvals: 1- max 12x15x4cm 2-material flame rated plastic UL-94-VO 3-max weight 4-self-powered from line (L-N up to 277V) connections 5-FCC conducted and radiated EMI 6-recessed screw terminal connections labeled A,B,C,N,G Functions:

1-those associated with concentrator functions

### **Future Functions:**

CT: Step-change time series using adaptive ARX-based load model CT: Step-change bin classifier to identify loads with one or more user-specified circuits Concentrator: Automated internal sumcheck tracking Concentrator: Other self-configuration and reliability features Concentrator: Link to existing utility meters (common AMR and PDA SIO options)

# Appendix B: Abu Dhabi CCP Portal Data

Abu Dhabi CCP Portal contains building characteristics data for each of the 995 buildings surveyed:

- 1. General Information:
  - Building ID number
  - Date and time of survey
  - Year built
  - Number of floors
  - Energy use Intensity (EI)
  - Percent of building used for residential purposes
  - Percent of building used for other purposes
  - Building name
  - Number of apartments which are:
    - o 1 bedroom
    - o 2 bedroom
    - $\circ$  3 bedroom
    - 4 or more bedroom
  - Number of restaurants
  - Number of non-restaurants (shops)
  - Other notes
  - Typology of building
  - Made from concrete? (y/n)
  - Predominant structural material (if not concrete)
  - Percent of windows glazed, glaze type, tint type, shade type, seal quality:
    - o Front
    - o Right
  - Number of exterior doors and seal quality
- 2. Chillers (manufacturer, refrigerant, air blockage, condition (dirty or clean) and cooling capacity)
- 3. Floor Information (number by type and use of cooling units on a sampling of floors)
- 4. AC Information (type, number, location, manufacturer, cooling capacity, refrigerant, cleanliness, condition, cleaning schedule)
- 5. Water Information (filtration and disinfectant if applicable)
- 6. Restaurant Information (number of seats and hours of operation per day if applicable)
- 7. Toilet Information (type, flush type)
- 8. Lighting Information (most common, second most common lighting type on a sampling of floors)
- 9. Water Storage Information (location of water storage, capacity and auto shutoff)
- 10. Thermostat Information (number of fan coils, air handle units, number of thermostats, location, temperature setting, thermostat type)
- 11. Meter ID Number(s)

## Appendix C: SAMPLING PLAN

Stratified Sampling Method- We adopt a sampling plan similar to ELCAP's in which building/occupant characteristics of interest are identified and used to ensure a representative sample. Note that the values or ranges enumerated in each dimension will depend on the descriptions and distributions present in the RTI survey sample. The residential sample includes the following primary characteristics:

Cooling type (split, central, district cooling, other)

Building type (villa, row house, high rise)

Number of units in structure (1; 2-4; 5-8; 9 or more)

Occupancy (renter; owner)

Secondary characteristics may include following:

Year built (before 1980; 1980-89; 1990-94; 1995-99; 2000-2004; 2005-2009; 2010-present)

Geographic location (Al Ain, Abu Dhabi)

Occupant income (under 100,000; to 200,000; to 400,000; over 400,000 AED)

For the Commercial/Institutional/Mixed-Use (CIMU) building sample primary characteristics include:

Building type (school, grocery with refrigeration, retail, office, mosque, hotel, clinic, hosp.)

Size (GFA ranges depend on type)

Cooling type (split, central, district cooling, other)

Number of stories

Secondary characteristics include following:

Year built (before 2000; 2000-2004; 2005-2009; 2010-present)

Geographic location (Al Ain, Abu Dhabi)

The CIMU sample comprises 996 buildings while the Chiller Optimization Pilot (CO-Pilot) sample comprises 40 buildings. Deployment of end-use monitoring equipment in the CO-Pilot buildings has several attractions:

1) End-use metering measures chiller input power directly but does measure the cooling loads directly. However if CO-Pilot measures cooling loads (even one-time measurements) the program will obtain a better understanding of plant efficiency by having both measurements made in the same set of buildings.

2) How distribution pump and fan loads are related to total cooling load has important implications for the CCP. Because these distribution loads are usually considered as a separate enduse from chiller plant, the CO-Pilot buildings provide opportunity for this analysis and resulting insights.

3) Electrical energy dissipated within the envelope translates directly to cooling load. The breakdown of these electrical internal gains into main components, such as lighting, IT equipment,

and plug loads, is of interest to the CCP. In the CO-Pilot buildings we will be able to analyze these loads in the context of total cooling load.

However, for load research purposes, it is important that the CO-Pilot sample be representative of the general population or at least of the CIMU sample. A preliminary analysis shows that his is generally the case.

Year of Construction. Figure B.1 shows frequency distributions of building age for the two samples. The COP sample is just a bit heavy at the mode (1995-1999) and a bit light in the 200-2007 cells. These discrepancies are small relative to the number of buildings for which age could not be determined (ND). The only serious difference is in the buildings built before 1990 but even this discrepancy is less than the ND numbers.

Number of Floors. Half of the CO-Pilot sample is over 15 floors (versus 12% of CIMU sample) making it distinctly "top-heavy" and the difference is made up entirely by the relative dearth of 1-to-5-story buildings. The intermediate heights, on the other hand, are well represented: the 6-10-story bin contains about 30% of both samples and the 11-15-story bin contains about 6% of both samples. The significance of these discrepancies will be assessed by analysis after collecting the first two or three months of end-use metering data.

Energy Use Intensity. The fraction of buildings with EUI>450kWh/m2 is about equal for the two samples at about 20% corresponding to 7 buildings in the CO-Pilot sample. It is not reasonable to expect the distribution among these seven to align much more closely with the five cells of the CIMU sample. Ideally we would have 19 and 10 instead of 15 and 14 in the 150-300 and 300-450 bins.

Building Type. The Commercial/Office Low-rise type is under-represented slightly (have 1, need 2) in the CO-Pilot sample. The Commercial/Residential Medium-rise type is more significantly under-represented (have 5, need 20) if the load-profiles or end-use distributions turn out differ substantially from those of the closely related Commercial/Residential High-rise type. The situation can be further assessed after analysis of two or three months data is completed.

Figures B.1 – B.4 have been updated as of June 2014 to reflect the 20 buildings in the current sample plan.



Figure B.1 Building age distributions: Survey sample (left) and Pilot sample (right). (N.D. means could not be determined)



Figure B.2 Building Height Distributions: Survey sample (left) and Pilot sample (right)



Figure B.3. Energy Use Intensity Distributions: Survey sample (left) and COP (right, please note that due to insufficient information, this has not been updated to reflect the 20 buildings sampled).



Figure B.4. Building Type Distributions: Survey sample (left) and Pilot sample (right)

## **Appendix D: Bluetooth Low Energy SoC Description**

The CC2541 is a power-optimized true system-on-chip (SoC) solution for both *Bluetooth* low energy and proprietary 2.4-GHz applications. It enables robust network nodes to be built with low total bill-of-material costs. The CC2541 combines the excellent performance of a leading RF transceiver with an industry-standard enhanced 8051 MCU, in-system programmable flash memory, 8-KB RAM, and many other powerful supporting features and peripherals. The CC2541 is highly suited for systems where ultralow power consumption is required. This is specified by various operating modes. Short transition times between operating modes further enable low power consumption.

The CC2541 is pin-compatible with the CC2540 in the 6-mm  $\times$  6-mm QFN40 package, if the USB is not used on the CC2540 and the I<sup>2</sup>C/extra I/O is not used on the CC2541. Compared to the CC2540, the CC2541 provides lower RF current consumption. The CC2541 does not have the USB interface of the CC2540, and provides lower maximum output power in TX mode. The CC2541 also adds a HW I<sup>2</sup>C interface.

The CC2541 is pin-compatible with the CC2533 RF4CE-optimized IEEE 802.15.4 SoC.

The CC2541 comes in two different versions: CC2541F128/F256, with 128 KB and 256 KB of flash memory, respectively.

### Hardware Features

- RF
  - o 2.4-GHz Bluetooth low energy Compliant and Proprietary RF System-on-Chip
  - o Supports 250-kbps, 500-kbps, 1-Mbps, 2-Mbps Data Rates
  - Excellent Link Budget, Enabling Long-Range Applications Without External Front End
  - Programmable Output Power up to 0 dBm
  - Excellent Receiver Sensitivity (–94 dBm at 1 Mbps), Selectivity, and Blocking Performance
  - Suitable for Systems Targeting Compliance With Worldwide Radio Frequency Regulations: ETSI EN 300 328 and EN 300 440 Class 2 (Europe), FCC CFR47 Part 15 (US), and ARIB STD-T66 (Japan)
- Layout
  - Few External Components
  - Reference Design Provided
  - $\circ$  6-mm  $\times$  6-mm QFN-40 Package
  - Pin-Compatible With CC2540 (When Not Using USB or  $I^2C$ )
- Low Power
  - Active-Mode RX Down to: 17.9 mA
  - Active-Mode TX (0 dBm): 18.2 mA
  - Power Mode 1 (4- $\mu$ s Wake-Up): 270  $\mu$ A
  - Power Mode 2 (Sleep Timer On):  $1 \mu A$
  - Power Mode 3 (External Interrupts): 0.5 μA
  - Wide Supply-Voltage Range (2 V 3.6 V)
- TPS62730 Compatible Low Power in Active Mode
  - RX Down to: 14.7 mA (3-V supply)

- TX (0 dBm): 14.3 mA (3-V supply)
- Microcontroller
  - High-Performance and Low-Power 8051 Microcontroller Core With Code Prefetch
  - In-System-Programmable Flash, 128- or 256-KB
  - 8-KB RAM With Retention in All Power Modes
  - Hardware Debug Support
  - Extensive Baseband Automation, Including Auto-Acknowledgment and Address Decoding
  - o Retention of All Relevant Registers in All Power Modes
- Peripherals
  - Powerful Five-Channel DMA
  - General-Purpose Timers (One 16-Bit, Two 8-Bit)
  - IR Generation Circuitry
  - 32-kHz Sleep Timer With Capture
  - Accurate Digital RSSI Support
  - Battery Monitor and Temperature Sensor
  - 12-Bit ADC With Eight Channels and Configurable Resolution
  - AES Security Coprocessor
  - Two Powerful USARTs With Support for Several Serial Protocols
  - 23 General-Purpose I/O Pins
    - $(21 \times 4 \text{ mA}, 2 \times 20 \text{ mA})$
  - $\circ$  I<sup>2</sup>C interface
  - o 2 I/O Pins Have LED Driving Capabilities
  - Watchdog Timer
  - Integrated High-Performance Comparator
- Development Tools
  - CC2541 Evaluation Module Kit (CC2541EMK)
  - CC2541 Mini Development Kit (CC2541DK-MINI)
  - SmartRF<sup>TM</sup> Software
  - o IAR Embedded Workbench<sup>™</sup> Available

### Software Features

- *Bluetooth* v4.0 Compliant Protocol Stack for Single-Mode BLE Solution
  - Complete Power-Optimized Stack, Including Controller and HostGAP – Central, Peripheral, Observer, or Broadcaster (Including Combination Roles)ATT / GATT – Client and ServerSMP – AES-128 Encryption and DecryptionL2CAP
  - Sample Applications and Profiles
    - Generic Applications for GAP Central and Peripheral Roles
    - Proximity, Accelerometer, Simple Keys, and Battery GATT Services
    - More Applications Supported in BLE Software Stack
  - Multiple Configuration Options
    - Single-Chip Configuration, Allowing Applications to Run on CC2541
    - Network Processor Interface for Applications Running on an External Microcontroller
  - BTool Windows PC Application for Evaluation, Development, and Test

## **Functional Diagram**



## **Related SoC Options**

Part Number	CC2541	CC2540	CC2541-Q1
Device Type	Wireless MCU	Wireless MCU	Wireless MCU
Flash size (KB)	128	128	256
RAM size (KB)	8	8	8
RX Current (Lowest) (mA)	17.9	19.6	17.9
Standby Current (µA)	0.5	0.4	0.5
Wakeup Time (PD $\rightarrow$ RX/TX) ( $\mu$ s)	500	530	500
Sensitivity (Best) (dBm)	-93	-93	-93