Title

Advanced Monitoring Technologies for the Evaluation of Demand-Side Management Program

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by Anibal T. De Almeida and Edward L. Vine

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ADVANCED MONITORING TECHNOLOGIES FOR THE EVALUATION OF DEMAND-SIDE MANAGEMENT PROGRAMS

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ABSTRACT

This report was commissioned by the California Institute for Energy Efficiency as part of its research mission to advance the energy efficiency and productivity of all end-use sectors in California. The aim of this study is to provide an assessment of the state-of-the-art technologies that can be used for monitoring and evaluating demand-side management (DSM) programs. Additionally, the study points out research, development, and demonstration projects whose implementation can contribute to a more accurate and cost-effective evaluation of the performance of end-use technologies.

During the past two decades, technology developments in the fields of microelectronics, computers and communications had a large impact on monitoring equipment. The improvements achieved led to the appearance of increasingly powerful, convenient to use, and flexible equipment, enabling a wider application of end-use metering at a lower cost. Equipment specifications are getting closer and closer to an "ideal" monitoring system: good accuracy, high reliability, moderate cost, large number of monitored end uses, large data storage capacity, flexible communications, non-intrusiveness, powerful pre-processing of data. This report briefly examines the following techniques that can be used for end-use monitoring: field test equipment, general purpose data loggers, run-time data loggers, utility-oriented data loggers, energy management systems, two-way communication, power line carrier techniques, direct and distributed load control, and non-intrusive load monitoring. The report concludes with recommendations for developing new measurement technologies, as well as additional research and development activities to support these efforts.

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1. INTRODUCTION*

This report was commissioned by the California Institute for Energy Efficiency (CIEE) as part of its research mission to advance the energy efficiency and productivity of all end-use sectors in California. The aim of this scoping study is to provide a brief assessment of the state-of-the-art technologies that can be used for monitoring and evaluating demand-side management (DSM) programs. Additionally, the study points out research, development, and demonstration projects whose implementation can contribute to a more accurate and cost-effective evaluation of the performance of end-use technologies.

Since the mid-1980s, utility companies have been very active in implementing DSM programs in response to regulatory direction from state public utility commissions to acquire DSM as a resource (NARUC 1988). In addition, several utilities in the United States now receive financial incentives for promoting energy efficiency (Reid and Brown 1992). The emphasis on cost-effectiveness tests by regulatory and utility organizations for examining utility program performance has also led to more evaluation activities. In conclusion, DSM programs have proliferated at an exponential rate, resulting in an increasing need for an accurate and independent assessment of DSM program savings.

The evaluation of DSM programs typically provides information on the energy and demand savings of these programs. Accordingly, the evaluation procedure must accurately assess the energy and demand performance before and after the implementation of the DSM program (see below). The feedback provided by program evaluation is essential for load forecasting and planning, as well as to correct the implementation of ongoing programs and to improve the design and implementation of future programs.

A few caveats need to be mentioned prior to reading the rest of this report. First, in this report, monitoring means assessing the performance of particular types of equipment (e.g., economizer, boilers), components of equipment (e.g., a cooling tower in a cooling system), systems (e.g., heating and ventilation), and/or whole buildings. Monitoring typically includes the measurement (metering) of energy usage. Second, this project was of limited budget and duration. Accordingly, the discussion that follows does not cover all technologies, equipment (e.g., BTU meters and portable flow meters), and manufacturers. We do provide some descriptions of the above, but only as illustrative examples (see Appendix B). We encourage readers to examine another report for a more comprehensive and detailed review of some of these products, which was prepared for the Electric Power Research Institute, Bonneville Power Administration, and the Center for Electric End-Use Data (Abbott et al. 1992). Third, the mention of specific products, vendors, or firms does not represent an endorsement by CIEE or Lawrence Berkeley Laboratory. Where available, we provide references to more comprehensive and/or more detailed studies in this area. Fourth, end-use monitoring technology is changing quickly, so that what we know today is surely to be quite different in the near future in terms of equipment costs and capabilities, and levels of

* A glossary is provided in Appendix A to assist people unfamiliar with some of the terms used in this report.

accuracy. Fifth, the focus of this report is on hardware. However, advances in software are also needed, including the development of industry standards for communication and software protocols, as well as the development of software for helping users select monitoring systems. And sixth, equipment cost can vary quite significantly, depending on the quantity of equipment purchased. Where available, we provide cost/unit for single-unit purchases and for bulk purchases.

The rest of this section provides a brief overview of the use of monitoring technologies and methodologies for DSM evaluation, what an ideal monitoring system would look like, and the evolution of end-use monitoring equipment. Section 2 focuses on established technologies that are currently used for end-use monitoring, in order to distinguish today's technologies from tomorrow's technologies. Section 3 describes established technologies that are underutilized in end-use monitoring but have a strong, near-term potential in being used for end-use monitoring (e.g., load control and energy management and control systems). Section 4 examines advanced end-use monitoring technologies, while Section 5 describes other technologies that offer the potential for integrating end-use monitoring with other value-added capabilities (e.g., two-way communication and building automation). These latter technologies are normally perceived to be outside the realm of demand-side management and end-use monitoring, but could become important source of end-use information. At the end of the paper, we offer some recommendations for further research activities in these areas.

1.1 Monitoring Technologies and Methodologies for DSM Evaluation

DSM programs can be evaluated using four methods: engineering models, statistical models (using whole building billing data), hybrid engineering/statistical models, and metering (Violette 1991). These methods result in different levels of precision and costs, with metering providing the highest precision and the highest costs. Normally, the most cost-effective evaluation procedure uses a combination of the above methods. Metering (in particular, end-use metering measurements made on a sample of customers) is used to validate, calibrate, and improve the estimates obtained through the use of less expensive methods (e.g., engineering models) (Violette et al. 1991; Xenergy 1990). End-use metering, if carried out before and after DSM program implementation, can provide more accurate estimates of energy and demand savings, the effects of fuel switching, and end-use load profiles. End-use metering can also measure small (absolute) savings and side effects, such as power quality disruptions and the interactions of lighting and cooling measures.

Metering costs can be minimized by a careful assessment of the required monitoring period. Some DSM measures may require short-term monitoring, such as monitoring operation schedules or the direct kW and kWh savings of improving the efficiency of lamps, ballasts and fixtures in a lighting project. However, if the interaction of lighting with the heating, ventilation and air-conditioning (HVAC) system needs to be investigated, long-term monitoring is required. The same will happen if daylight controls are used. And the assessment of the persistence of energy savings requires even longer term monitoring (e.g., over the lifetime of the DSM measure).

The cost of end-use metering has been the major barrier to its greater use. Besides being more expensive than other methods, end-use metering also has other limitations:

- In order to conduct before and after metering, the DSM program may need to be postponed, in order that the "before" metering is carried out. This may take too long, in which case a control group of participants can be used instead. However, in some programs, such as those with a high market saturation, the identification of a suitable control group is difficult. As an alternative, certain types of load control can be used to avoid the need for pre-metering or the need of a control group, as discussed below.
- The length of time required to collect the data may be long, ranging from a few months to a year, depending on the application.
- When some factors (e.g., weather) influence loads, "after" metering is required to normalize the results.
- End-use metering at short intervals for a large number of customers generates an enormous amount of data that must be processed for analysis. Local pre-processing of these data can mitigate this problem.
- The results of metering may be subject to bias because of the nonrepresentative behavior of volunteer participants in DSM programs (self-selection bias) and with the change in behavior of consumers due to their awareness of being metered.

In addition to reducing the cost of end-use metering, other options need to be explored which can be used to provide the metered data as well as other functions. For example, two-way communication, energy management and control systems, and building and home automation are some examples where end use data can be collected and used for monitoring and evaluating DSM programs. The need for these kinds of technologies and others is expected to increase as the utilities' demand for end-use monitoring increases.

1.2 End-Use Monitoring Capabilities

Based on our review of the literature and discussions with experts in the field, an ideal monitoring system in the residential and commercial sectors would have the following capabilities:

- Capability to monitor at least six end uses, in addition to whole building data.
- Capability to handle 16 data collection channels.

- Programmable time intervals for collecting data, below and above 15 minutes.
- Capability to collect energy-related data such as temperature, and water or gas flow.
- An accuracy level of +/- 2% for kWh, +/- 2°F for temperature, and +/- 15 seconds for the recorded time.
- Flexible data retrieval means (serial interface, optical port, power line carrier, telephone).
- Communication and data formats similar to ones currently used by the utilities.
- Minimum of 36 days of recording capacity and a minimum of 1 year of data protection in the event of a power failure (5 years for a lithium battery).
- Minimum installation inconvenience for the consumer. Ideally, the system should be non-intrusive.
- Moderate cost (equipment and installation), with $5-8,000 being a reasonable upper bound.

This type of configuration has been achieved in at least one utility project: Pacific Gas and Electric's Commercial End-Use Metering Project (CEMP), where Synergistic C-190 data loggers were used (personal communication from Roger Lippman, National Center for Appropriate Technology, Oct. 16, 1992).

1.3 Technological Evolution of End-Use Monitoring

This report assesses advanced (state-of-the-art) monitoring technologies for DSM evaluation, emphasizing technologies that have the potential to achieve a wider application of end-use metering at a moderate cost. The performance/price relation has improved significantly during recent years. Appliance energy monitoring has evolved through several generations of equipment:

- Dedicated data recorder (chart recorder, magnetic mass storage, semiconductor memory) for each single appliance.
- Multi-channel data loggers hardwired to individual transducers connected to each appliance.
- Multi-channel data loggers in which the central unit communicates with the individual transducers connected to each appliance via a power line carrier through the building wiring.
- Non-intrusive load monitoring techniques, where monitoring of the whole load is done at a single point adjacent to the meter. The end-use consumption of individual appliances is estimated using sophisticated pattern recognition

algorithms.

- A likely scenario in the near future is the penetration of home/building automation and two-way communication systems. These technologies allow the utility to continuously monitor end-use energy consumption of loads with smart controllers without any specific additional investment. This means that the monitoring of energy and demand savings of all customers is now possible. Because the hardware infrastructure (communication network, controls, and metering) required for end-use metering will be used to provide many other services, the scenario described can be not only cost-effective, but also bring substantial performance improvements in communication and control.

2. OVERVIEW OF ESTABLISHED MONITORING TECHNOLOGIES

This section of the report presents a brief overview of established technologies that can be used for monitoring end-use energy consumption. A more detailed description (manufacturers, models, and main characteristics) of these types of equipment can be found in Abbott et al. (1992).

2.1 Field Test Equipment for Power Monitoring

Portable field test equipment is used for energy auditing and for short-term, end-use monitoring. Constant (fixed duty cycle) loads may only need short-term measurement, and short-term field testing can provide the cheapest solution for that purpose. These units normally feature clamp-on current transformers for easy connection. Low-end field equipment includes single-phase power meters, without data recording capabilities, costing in the range of \$200 to \$1,000. The costs vary, depending on the accuracy, true RMS voltage, and current measurement capabilities (possibility of giving correct readings with distorted waveforms).

High-end field equipment includes three-phase power analyzers that measure extensively the electrical variables associated with the energy conversion process (true RMS currents and voltages in the three phases, power, reactive power, power factor, energy, reactive energy). The more advanced units can also perform harmonic analysis. These units normally have data recording capabilities that can be programmed in the front panel. Some of the units feature a built-in graphics recorder or a liquid crystal display (LCD) panel to display the waveforms as well as the values selected in the keypad. The power analyzers are normally available with a serial interface for dumping the data into a computer or portable terminal. Power analyzers cost in the range of \$4,000 to \$10,000, depending on accuracy and power measurement capabilities.

One type of field test power measurement equipment that is commercially available measures power, current, and voltage in the three phases, as well as the field efficiency of motors. This is done by processing the measurements with special purpose software that calculates efficiency indirectly by estimating the total motor losses from the measurements taken. However, there is a need to develop equipment able to measure the field efficiency of other types of important loads, such as HVAC loads (Misuriello 1991).

2.2 General Purpose Data Loggers

General purpose data loggers have experienced a substantial evolution during the last decade benefiting from improvements in the field of micro-electronics. Powerful microprocessors, very high density memory, and integrated analog front-ends made possible the appearance on the market of compact, portable, reliable, and fairly inexpensive data loggers. The main reasons for the increase in reliability in modern data loggers are due to the lack of moving parts and the use of low-power electronic components (i.e., there is no need for a cooling fan).

Typically, the units used for energy monitoring have the following capabilities:

- Multi-channel analog front-end, including signal conditioning, multiplexers and analog-to-digital converter.* The data inputs (normally in the range of 8 to 256 input channels) are digitized with a 12-bit resolution. The 12-bit resolution allows the discrimination of small changes and accommodates variables having a wide range of values. The data loggers are normally able to cope with programmable sampling rates (from a few Hz to several tens of kHz). Some variables may require low sampling rates (e.g., temperature), while other variables may require fast sampling rates (e.g., harmonic current measurement).
- Multi-channel digital inputs, normally opto-isolated, which receive information from pulse-emitting transducers and which indicate the operating status or conditions of parts of the system being monitored. In the latter, each channel provides simple information - "on/off" or "open/closed" - such as the status of an appliance or the position of a damper.
- Microprocessor that can control the data acquisition process and perform preprocessing of the data. Normally, data acquisition routines are supplied, but signal processing is not part of the system.

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*Analog inputs are used to measure continuously varying variables such as temperature, fluid flow, solar radiation, electric power, current and voltage, receiving the signal from suitable signal transducers. Some transducers may be placed inside the data logger case, while other transducers are connected to a block of terminals or to special sockets on the outside of the data logger case.

- The program is stored in non-volatile memory (EPROM or EEROM).
- Capability of a local set-up, either with a keypad/display combination, or with a portable terminal connected to a serial interface.
- Data storage, either of non-volatile type (EPROM or EEROM) or, in most cases, RAM with battery back-up protection, which is used to store the data. There has been a drastic reduction in price per bit of semiconductor memories accompanied by an exponential increase in memory density. Typically, modern data loggers have between 32 kBytes and 1 MByte of memory.
- Built-in modem for remote metering of the data through the telephone line. The units can either be interrogated, or they can be programmed to transmit data at certain times. Some manufacturers offer the possibility of remote programming of the units. Some units can also be daisy-chained and connected to the same phone line.
- Some manufacturers offer, normally as an option, opto-isolated digital outputs that can be used for alarms or controls.

General purpose data loggers can also be provided by a personal computer. There are a wide variety of data acquisition boards on the market able to meet most requirements. PC-based units have the following features: (1) they can receive communication and control cards, as well as perform advanced data analysis and display; (2) they are more appropriate for sites where there is a frequent interaction with users; and (3) they are more powerful than stand-alone data loggers, but do not have the same robustness. In this case, robustness is the capability of operating in an adverse environment (wide temperature and humidity variations, resistance to shock and vibration) without affecting system reliability. The absence of moving parts, the low power consumption, and the possibility of using a totally enclosed box, can make some types of general-purpose data loggers very robust. On the other hand, because personal computers are unwieldy, often lack battery backup, and have fans that get dirty, personal computers may be best used for laboratory use rather than in the field.

The price of a general-purpose data logger with the characteristics mentioned above typically falls in the range of $1,500 to $3,000, depending on the amount of memory, number of channels, and signal conditioning requirements. A recent survey of equipment characteristics, including prices, is presented elsewhere (Abbott et al. 1992). Installation costs can be significant due to the labor required to install the transducers and the dedicated wiring. Also, the installation process is an intrusive procedure and may not be accepted by some consumers.

In contrast to utility-oriented data loggers that have built-in power transducers, general purpose data loggers measure electric power by receiving the pulses of a kWh meter with pulse initiating capabilities, or by using external power transducers. These transducers, which provide an analog output proportional to the power, typically cost in the range of $200 to $500, depending on the number of phases and the level of accuracy.

2.3 Run-Time Data Loggers

Run-time data loggers are used for monitoring loads whose power does not change while they are on. In some DSM programs (e.g., lighting programs), it is important to know the operating time of the loads, as the power consumed can be inferred by the number of operating hours. These type of data loggers are fairly inexpensive, gathering data with an installed cost in the range of $150 to $400 per metered point. Some units on the market record the on/off profile continuously, while other units only count the number of operating hours or the number of switching cycles (see Appendix B). This last feature can be particularly useful to investigate the effect of duty cycling on equipment lifetime. Run-time data loggers can monitor the operating state of the load either by using a current transformer (all types of loads), a photocell (lighting), or even by sensing the stray magnetic field with a pick-up coil (motors).

2.4 Utility-Oriented Data Loggers

The expanding requirements for end-use monitoring have created a market for data loggers especially designed for that purpose. These units have the characteristics of general-purpose data loggers, but differ from them in one important aspect: they have built-in power transducers, which reduces monitoring costs. Besides power, other metered quantities include apparent power, energy, reactive energy, RMS current, RMS voltage and power factor. To monitor the consumption of appliances, the user only needs to install the current transformers (normally of the split-core or clamp-on types), leading to lower installation costs.

Utility-oriented data loggers also feature digital inputs that can be used for pulse counting from utility meters and for status monitoring. The information provided by status monitoring can be used to measure equipment run-time and the number of on/off cycles. Other variables, such as temperature, humidity, and process flows, can be measured using the analog inputs.

As with general-purpose data loggers, utility-oriented data loggers may also incur substantial installation costs, besides the inconvenience of the intrusion in the customer premises. The equipment cost is typically in the range of $2,000 to $4,000 depending on the number of channels and power transducers. The specifications of these kinds of units can be found in Abbott et al. (1992). Some manufacturers make multi-channel data recorders that are interfaced with rotating disk kWh meters having pulse initiation capabilities, which register the power consumption by recording the pulses (Abbott et al. 1992). Units with pulse reading capabilities normally feature a modem for remote communication and cost in the range of $500 to $900 for a four-channel unit.

3. NEAR-TERM MONITORING OPPORTUNITIES

3.1 Energy Management and Control Systems (EMCS)

The use of energy management and control systems (EMCS) with whole building data has a very large potential for estimating end-use load profiles, as many large and medium-sized commercial buildings have already installed metering equipment that collect energy consumption at periodic intervals (typically, every 15 minutes to one hour). Engineering algorithms and/or statistical methods can be used to disaggregate the whole-building data into primary end uses, taking into account the weather dependency of the loads, on-site equipment, and operating schedules (Eto et al. 1991; Violette et al. 1991; Xenergy 1990; Akbari 1989; Flora 1986). A small end-use metering sample can be used to calibrate the estimates provided by the disaggregation procedure.

Since the EMCS can control some loads and provide information on the status of loads, it is possible to measure the power of constant loads by measuring the step change in the total load value. These tests could be done at non-critical times (e.g., outside working hours), and values should be normalized as a function of the voltage level. These values could reduce the required amount of end-use metering.

In order to optimize building energy use, an EMCS can be connected to distributed sensors in the building. The combination of sensors with a power line carrier can substantially reduce the installation costs of the monitoring system (Quadlogic 1990). The distributed sensors allow the detection and analysis of potential savings opportunities as well as the implementation of sophisticated strategies. For example, the optimal implementation of a real-time pricing system with an EMCS requires detailed sensing of controllable loads (Daryanian 1991). The same sensors can be used for end-use monitoring.

The key advantages of EMCSs are: (1) cost - they can take advantage of hardware installed for other purposes (e.g., control); (2) access to status and temperature information that is not normally collected due to cost; and (3) accessibility of data to building operating staff. The key disadvantages of EMCSs are: (1) the data are often recorded as change-of-variable instead of a fixed-time interval; (2) insufficient trending channels; and (3) operators may enhance configuration and interfere with data acquisition.

Although EMCSs are attractive for end-use metering, some utilities do not permit the use of EMCSs for building monitoring due to the responsibilities and potential liabilities involved (Northeast Utilities 1990). Specifically, comfort and working conditions may be affected if the EMCS malfunctions and, in case this happens, the utility wants the owner to assume full responsibility and liability, rather than the utility. Accordingly, very few EMCSs have been used to monitor loads, but the potential remains.

Guidelines have been developed for evaluating particular sites to determine if an EMCS can be used for monitoring (Heinemeier and Akbari 1992). The guidelines also discuss how to find out if the necessary elements are present, and what to do if they are not. The guidelines could also form the basis for specification of future generations of EMCSs that will include monitoring as a basic function, or monitoring modules that that could be used to supplement existing EMCSs. The authors assert that these guidelines could be easily met with minor software changes by the manufacturer within their existing trend facilities.

3.2 The Electric ARM*

The Electric ARM (Appliance Research Metering) is suitable for monitoring the consumption of individual loads, either in residences or small commercial buildings. The system block diagram is represented in Figure 1. The ARM includes a central receiver/recorder and load-sensing units. The receiver/recorder, placed next to the consumer meter, receives information using power line carrier communication from the loads' transponders (up to 8 transponders can be used with a single receiver). The transponders are watt transducers that measure instantaneous power and send the load profile to the receiver/recorder. For hard-wired appliances (e.g., water heater or central air-conditioner), current transformers have to be inserted in the distribution panel to enable the current measurement of the transponders. Transponders that monitor plug-in appliances (e.g., refrigerator or washing machine) are easier to install, since they are placed between the appliance's plug and the wall socket. If the existing meter has a pulse initiating circuit, its pulses are fed to the receiver/recorder. Otherwise, there is a need to install a watt-hour transducer next to the meter that measures the whole load.

The Electric Arm features a reliable communication system. Each message between the receiver and transponder contains the identification code of the transponder, and a Cyclical Redundancy Check is used. Once every minute, the transponders send 10 minutes of load profile data (taken with 9-second measurement intervals) to the receiver. This means that the same load period is sent 10 times (9 times redundant), which allows the suppressing of data contaminated with noise.

The recorder is a solid-state recorder and includes up to 128 K Bytes of semiconductor RAM memory with battery back-up. The data can be read with a portable terminal through an optical port, or the recorder can be read remotely via the telephone.

The typical equipment cost of the Electric ARM is around $3,000-$3,500 for monitoring six independent loads. The incremental cost for each additional load is $400. Installation costs depend on the number of hard-wired loads, which require an electrician to connect the transponders.

The Electric ARM has been commercially available since the mid-1980s, and California utilities (Pacific Gas and Electric Company and Southern California Edison Company) are using the Electric ARM for end-use load research.

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* Information about the Electric ARM can be obtained from Dan Hollow, Appalachian Technologies Corporation, P. O. Box 7303, 9109A Forsyth Park Drive, Charlotte, NC 28241.

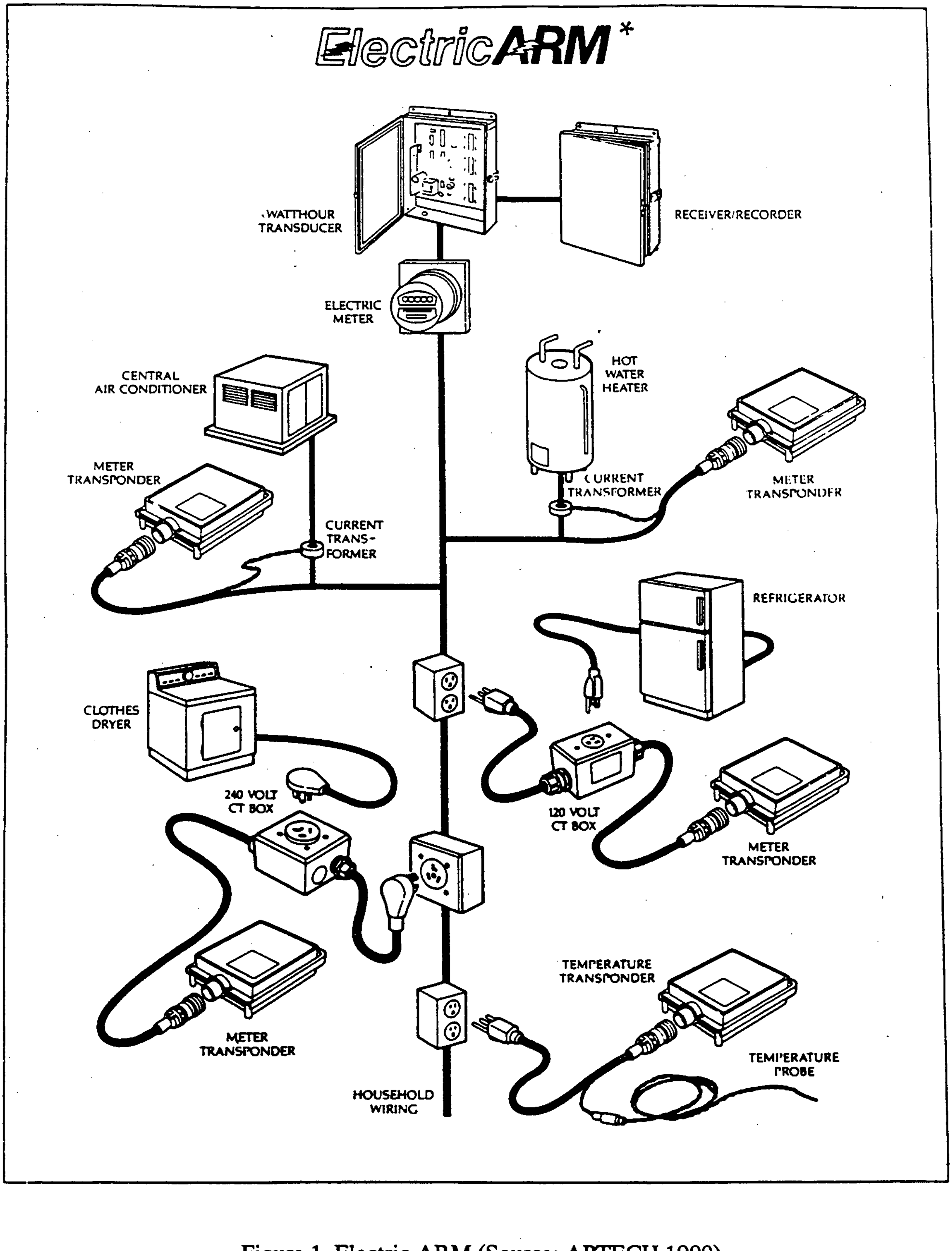

Figure 1. Electric ARM (Source: APTECH 1990)

4. ADVANCED TECHNOLOGIES FOR END-USE MONITORING

Since the late 1970's, the Electric Power Research Institute (EPRI) has sponsored the development of technologies for monitoring end-use loads. Two EPRI projects have resulted in advances in technologies for end-use monitoring: (1) the LCES (Load Control Emulator System), and (2) the NIALMS (Non-Intrusive Appliance Load Monitoring System).

4.1 The LCES*

The Load Control Emulator System (LCES) is an energy monitoring and control system designed to test advanced load management functions and collect load research data in residential or small commercial buildings. Within a building, the LCES uses bi-directional power line carrier (PLC) communications between the appliance modules, the user interface unit, and the central processing and data storage unit. The in-building system communicates with a central computer at the utility's offices through the switched telephone network, using a 2400 baud error-correcting modem.

The main purpose of the LCES is to enable a utility to implement load control strategies in a pilot program, collect load research data to evaluate candidate strategies, and easily modify control strategies, if needed, to obtain better results. The LCES can implement direct, local, and distributed load control options. Price-responding strategies (e.g. real time pricing, peak-activated rates), adaptive thermostat, appliance interlock, load factor management, interruptible, duty cycle limiting, and load leveling strategies are available.

The LCES provides 5-minute load data for total premise energy use and individual appliance energy use, as well as recording indoor and outdoor temperatures, thermostat settings, and customer actions (changing thermostat setting, changing end-use load control priorities, reviewing historical energy use and costs, etc.)

Figure 2 shows the LCES configuration. The LCES is composed of four subsystems:

(A) Through telephone communications, the Central Control Unit (CCU) at the utility can:

(1) send load management controls (on/off switching of loads, changes in rates, and remote programming of controls), and

(2) read end-use load profiles, temperatures, and customer interactions. The CCU requires an IBM-compatible 386 or higher PC.

* Information about the LCES can be obtained from Lawrence Markel, Electrotek Concepts, Inc., 10305 Dutchtown Road, Suite 103, Knoxville, TN 37932.

Load Control Emulator System

Remote Field Unit

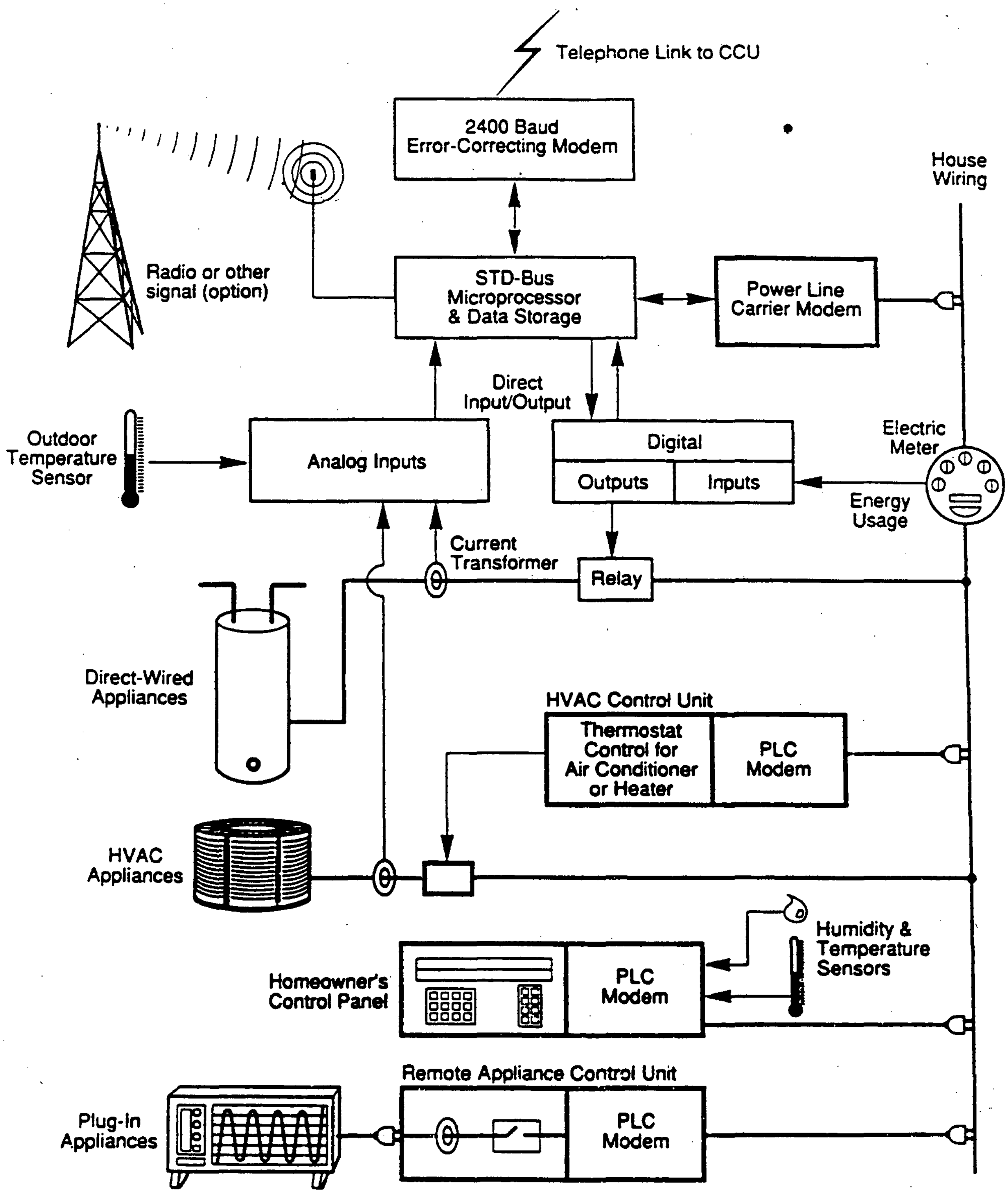

Figure 2. Load Control Emulator System (Source: Electro-tec Concepts 1990)

(B) The Remote Field Unit (RFU) commands (according to instructions received from the CCU) the control modules associated with individual appliances, and collects consumption data from up to 15 appliance modules via PLC communications.

(C) There are several types of remote control units. The Remote Appliance Control Units (RACU) contain a current transducer and a control relay. There are modules for hard-wired and plug-in appliances. An HVAC module controls the thermostat for space heating and air conditioning as well as monitoring the HVAC load. A service panel remote monitors the premise's current, voltage, power consumption, and outdoor air temperature.

(D) The Homeowner's Control Panel (HCP) monitors temperature and displays messages (e.g., controls that are in effect) and price signals to the customer. The HCP also accepts inputs from the customer: for example, thermostat settings, on/off schedules for appliances, and appliance priority settings. The customer can review his past hour's, day's and month's energy usage and costs (total premise and individual appliance). If permitted by the utility, the customer can use the HCP to override the control strategy. All customer interactions with the HCP are recorded by the RFU.

The LCES is not yet in commercial production, and only 40 units have been installed. The Residential Energy and Load Management System project in New York (involving four local utilities, EPRI, and the Empire State Electric Energy Research Corporation) used 20 units. Additionally, five units each were tested by Public Service Indiana, Arizona Public Service Company, and Southern California Edison Company. The price of the LCES for a typical house (for a small quantity of units) is around $5,000. The target price for medium-scale production (100 quantity) is about $2,000. The incremental equipment costs for additional appliances are in the $200 - $300 range.

4.2 The NIALMS*

The NIALMS (Non-Intrusive Appliance Load Monitor System) was developed by the Massachusetts Institute of Technology (MIT) in 1984, under contract from EPRI, to provide information about the load profiles of individual appliances without submetering them. The NIALMS can be placed unobtrusively between the meter and the meter socket (Figure 3) There is no need to place wiring and transducers inside the customer premises.

The individual load profiles are estimated by analyzing the global load diagram of the consumer, as described below. Let us first consider loads with two operating state conditions (ON and OFF). Each appliance is characterized by consuming a certain amount of active and reactive power (Figure 4),

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* Information about NIALMS can be obtained from Larry Carmichael, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94304.

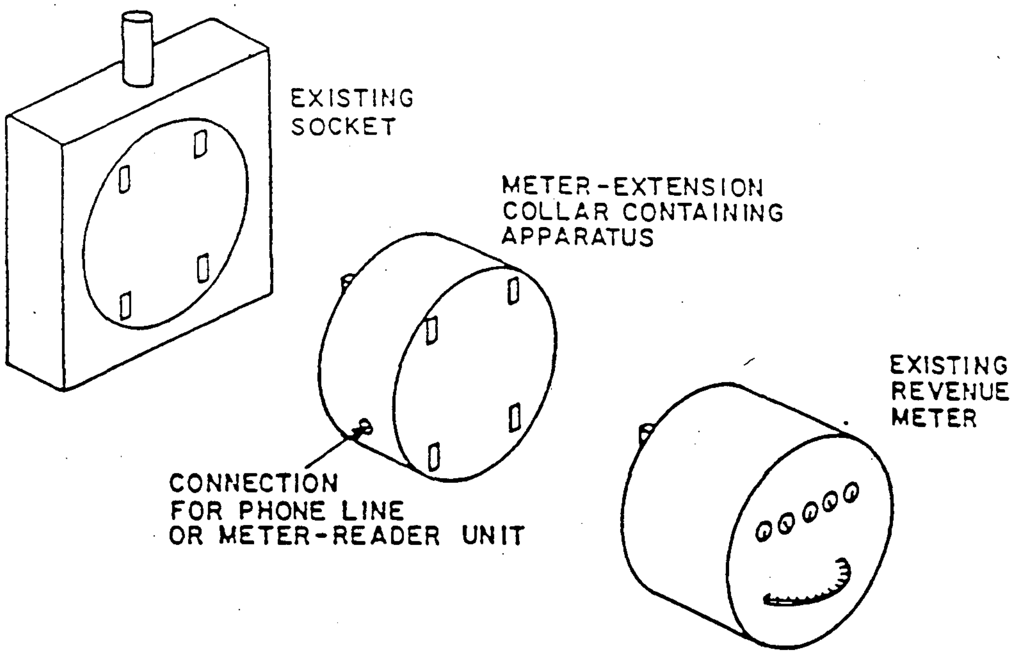

Figure 3. Mounting Structure of the NIALMS (Source: Hart 1991)

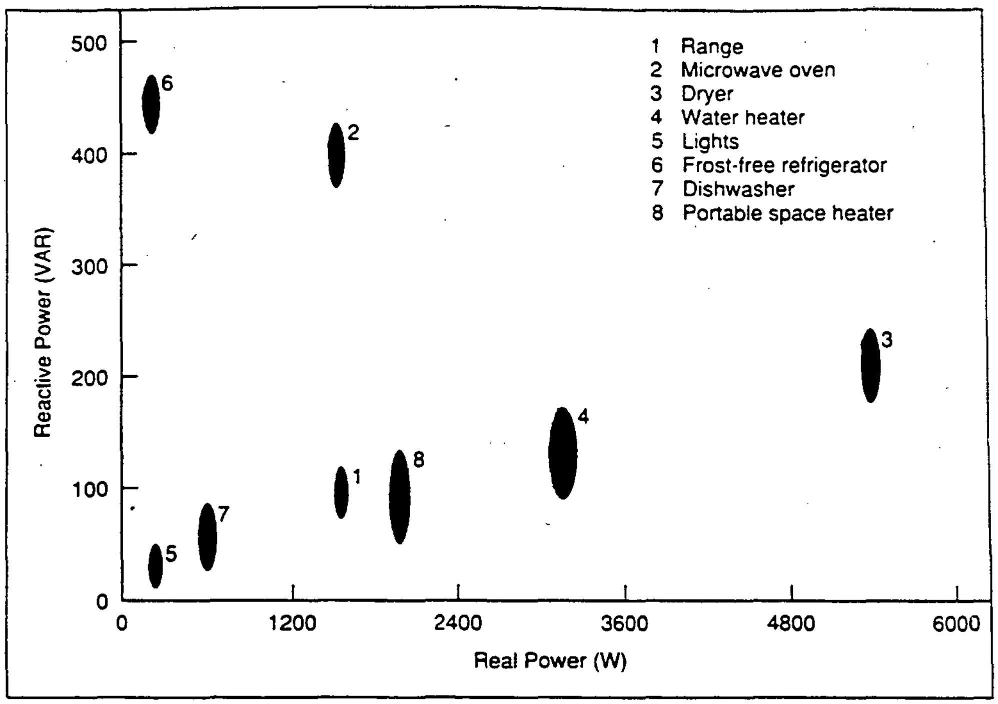

Figure 4. The NIALMS Mapping of Appliance Signatures

and, therefore, it is possible to identify which load is turned off or on, by looking at the step transitions of the global load. The NIALMS samples the load every second, and step changes that exceed a certain threshold are analyzed with pattern recognition algorithms. In order to achieve a higher accuracy, the step changes are adjusted as a function of the voltage level. The only intrusion in the customer premises is a brief, one-time visit to identify which appliances are present and obtain their respective signatures. During the visit, the appliances are manually turned on and off, in order to observe their signatures.

A second version of the NIALMS is self-learning with respect to identifying the appliances inside the house. This avoids the one-time visit. The self-learning process can be achieved by examining a data base that links power and reactive power consumption to the appliance type. Additionally, the voltage level (either 120 V or 240 V) and the duration statistics are used in the identification process. This automatic set-up version of the NIALMS, when successfully commercially implemented, will save set-up time and avoid the inconvenience of the one-time visit. This version can also automatically identify changes in the appliance stock.

Field tests of the automatic set-up version of NIALMS have been carried out with ten prototypes (five units by Rochester Gas & Electric and five units by the New England Electric System) to test the accuracy of NIALMS. Large two-state residential appliances were characterized with an error in the 5-10% range. In the field testing of NIALMS, the following limitations were discovered:

- Multi-state appliances generally led to higher errors: 16% for frost-free refrigerators and 47% for cooking ranges. However, other multi-state appliances (e.g., dishwashers, clothes dryers, and washing machines) were identified with errors below 10%.
- NIALMS cannot identify continuously varying loads (e.g., variable speed heat pumps and air conditioners), since they do not produce steep load changes.
- Due to noise being present in the line and voltage fluctuations, only appliances above 100 Watts can be identified. Although NIALMS was able to identify lighting with an error of 15%, NIALMS was not able to identify individual lights.
- NIALMS cannot identify the standby consumption of appliances like VCRs, clocks, microwave ovens, bell transformers, etc.

Until recently, the field units have only data recording capabilities, and the data processing is conducted at a central computer. However, the appearance in the market of powerful and inexpensive microprocessors makes feasible the availability of NIALMS with data analyzing capabilities.

EPRI is now in the process of selecting the manufacturer of NIALMS. The unit target price is in the range of $2,000-$2,500. The commercial unit will probably analyze the data and communicate the individual load profiles to the utility via telephone or through a power line carrier. Present work is directed at monitoring multi-state appliances (Hart 1991). Frost-free refrigerators (which have a compressor, a heater and a fan for a short defrosting cycle) have already been successfully monitored.

Compared to residences, commercial and industrial buildings have a larger number of loads and sometimes a larger diversity of loads. Step changes do not appear to suffice to identify individual loads in these kinds of buildings. The research work at MIT is directed to extending NIALMS to commercial and industrial buildings, by doing fast sampling at around 2 kHz and analyzing transient waveforms. The idea is to supplement the step change information with the transient signature. The start-up transients of motors, computers, electronic ballasts, magnetic ballasts, and other building loads are unique and, theoretically, it is possible to identity each type of load.

Because commercial and industrial buildings do not pose the same non-intrusiveness requirements as in houses, and because of the larger number of loads to be monitored in these kinds of buildings, it is possible to have several NIALMS to characterize sections of the facility. Most loads used in commercial buildings and industry generate harmonics that are typical of each load type. For example, a NIALMS in the lighting feeder can measure the load in magnetic ballasts lamps, electronic ballasts lamps, and compact fluorescents based on harmonic signatures (de Almeida 1991). Unless there is a large number, compact fluorescent lamps (CFLs) are difficult to identify because of their low power rating. However, CFLs produce a relatively large harmonic current that can be used to track their behavior. The identification and tracking of continuously variable loads is an important research direction. Harmonics may be useful to identify continuously varying loads, such as variable speed drives and dimmable electronic ballasts.

Loads that are difficult to identify, because of their large number or because of other loads with similar behavior, can be "marked." This may involve adding to the load a small circuit (e.g., a capacitor) or an harmonic-tuned filter component (the filter selectively removes a higher order harmonic), which consumes no power but is able to either change the reactive power or the harmonics consumed by the appliance, leading to improved possibilities of identification.

5. ADVANCED METERING AND COMMUNICATIONS FOR ENERGY MONITORING

5.1 Technological Developments in Communications

Technological developments in the fields of telecommunications, micro-electronics, and computers during the past two decades offer dramatically improved possibilities in communication and metering. Improved communications allow sophisticated control and metering activities, providing the capability to meet most DSM measurement requirements, including end-use monitoring.

For many years, existing one-way communication systems have provided reliable service for rate-setting purposes and load management. The most widely used technologies for this purpose are ripple control (low frequency line carrier) and radio broadcast. Simple on/off control of loads is possible. However, implementation of dynamic tariffs is cumbersome with conventional meters because there are only a few registers available, and remote reading of the meters is impossible with one-way communication. If smart meters are used with one-way communication, dynamic tariffs can be implemented, but the utility cannot have feedback to see if the right tariff is being applied by the meter.

Two-way communication networks, in which the electricity meter is a low level intelligence device (smart meter), offer improved capabilities and should be able to perform the following tasks:

- Collection of end-use load data for demand-side evaluation, rate setting, load forecasting, and planning.
- Providing information and guidance to customers (e.g., announcements).
- Load control.
- Tariff management (e.g., dynamic tariffs, remote meter reading, and automatic printing of bills).
- Distribution automation (e.g., sectionalizing isolator control, automatic breaker reclosure status monitoring and control, power factor compensation, voltage level regulation, event recording, and outage detection).
- Detection of meter tampering, fraud, theft, and meter failure.
- Monitoring the quality of supply (e.g., voltage level, phase symmetry, and harmonics).

For residential households, cost-benefit analysis shows that it is important to maximize services with the proper hardware. For example, utilities wishing to increase revenues can offer the following "value-added services" in addition to end-use monitoring objectives: (1) control of street lighting, (2) reading of water, gas, and district heating meters, and (3) warning of theft, fire, flooding, and gas leaks. Also, time-differentiated tariffs (and especially dynamic tariffs) can help to flatten load curves: charging higher prices at peak hours will provide an incentive for households and businesses to shift energy use to off-peak hours. New communication and metering techniques can enlarge the scope of application of dynamic tariffs to small industrial consumers, the service sector, and domestic consumers.

The choice of the most appropriate communication system (power cable, telephone, integrated signal digital network, cable TV) is a critical one. Many utilities are evaluating different communication technologies to implement two-way communication with their customers. The choices vary by cost and reliability. No single communication technology has a price advantage, and each is best suited for different situations, as discussed below.

In *high density* areas (e.g., urban areas), a comprehensive system is normally implemented using a proprietary network. This is normally implemented with a distributed power line carrier on the low voltage side. There is a lot of activity in the area of power line carrier technology: the systems being demonstrated include low frequency, high frequency, and mixed (low/high) frequency types. The path between the distribution transformer and the utility can be implemented in several ways (such as telephone, radio, and cable). In the U.S., the use of Ultra High Frequency (UHF) radio for this purpose is receiving considerable attention. For consumers located in *low density* areas (e.g., rural areas), a telephone link is the most cost-effective choice.

High bandwidth networks (e.g., fiber optics) can also be used to implement two-way communication systems, integrated with power cables to provide a comprehensive DSM system, cable TV, and telephone services. For instance, the integrated signal digital network (ISDN) can be used to transmit simultaneously data, images, and voice. ISDN is gaining worldwide acceptance as the next big step in communication networks. Some analysts foresee that ISDN will achieve a market saturation during the first quarter of the 21st century similar to the saturation of today's telephones. Due to its cost, the penetration of ISDN will be faster in commercial and industrial buildings. As ISDN requires a very large investment, there will be a need for coordination among the different companies using the common network (e.g., utilities and telecommunication companies).

The key to cost-effective two-way communication systems is the development of highly integrated systems, instead of specific equipment for specific tasks. An important area is the standardization of DSM systems. Standardization of protocols and interfaces, in which international cooperation is essential, will ensure the appearance on the market of open communication systems that can integrate equipment made by different manufacturers, as well as increase the likelihood that the system will remain compatible with equipment developed in the future.

5.2 Smart Meters

Smart meters already developed include all solid-state units and hybrid units (solid state and electro-mechanical) that are coupled to the existing rotating disk (Ferraris) meter, from which they receive the pulses. Although all solid-state meters currently cost 10 to 20 times the cost of their electro-mechanical counterparts, mass-production of all solid-state meters has the potential of offering prices lower than conventional meters.

Existing rotating disc meters (both single phase and three phase) can be converted to hybrid meters by retrofitting the electronic modules inside the meters. These microprocessor-based modules perform energy monitoring by counting the rotations of the disc in a programmed time period, typically between 5 and 15 minutes. The energy and demand data can be read with a general purpose data logger that is coupled to the meter through an optical port. Some hybrid meters have a serial interface that can be coupled to a telephone modem for remote communication. The price of the modules lies in the range of $120 to $250, depending upon the memory available and the communication capabilities.

All-solid-state smart meters use powerful microcomputer chips, featuring a wide array of measuring, communication, and control capabilities. Typically, all-solid-state meters sample the voltage and current waveforms with a sample rate (around 1kHz) to perform instantaneous calculations of the active and reactive power. The minimum and maximum values of the above quantities, as well as the time of occurrence, can be stored. The meter can be programmed to register the readings at intervals ranging from less than one minute to one day. Meter programming (for time-of-use rates or for data collection) and meter reading can be done with a portable terminal via the optical port on the front of the unit or remotely (typically either via a radio/power line carrier communication system or a telephone line).

The real price of electricity fluctuates instantaneously, due to stochastic variations in supply and demand. New and inexpensive metering devices coupled with two-way communication have the potential to cost-effectively implement real-time prices and convey to consumers the most appropriate price signals. Additionally, new metering technology includes the possibility to provide consumers needed information in a way that is easily understood. In order that time-variable tariffs work, the consumer needs to know about the tariff program and the times when rates change. Therefore, smart meters should have the ability to convey to the consumer the times when price changes occur, as well as price levels. See Appendix B for a description of the main characteristics of some electronic meters on the market, as well as associated two-way communication systems.

6. LOAD CONTROL TECHNIQUES FOR DEMAND-SIDE MANAGEMENT AND MONITORING

For many years, utilities have conducted load control programs. DSM programs that use load control techniques may also be able to use these techniques for monitoring purposes, as discussed below. Control techniques can be classified as: direct load control, local load control, and distributed load control (Figure 5).

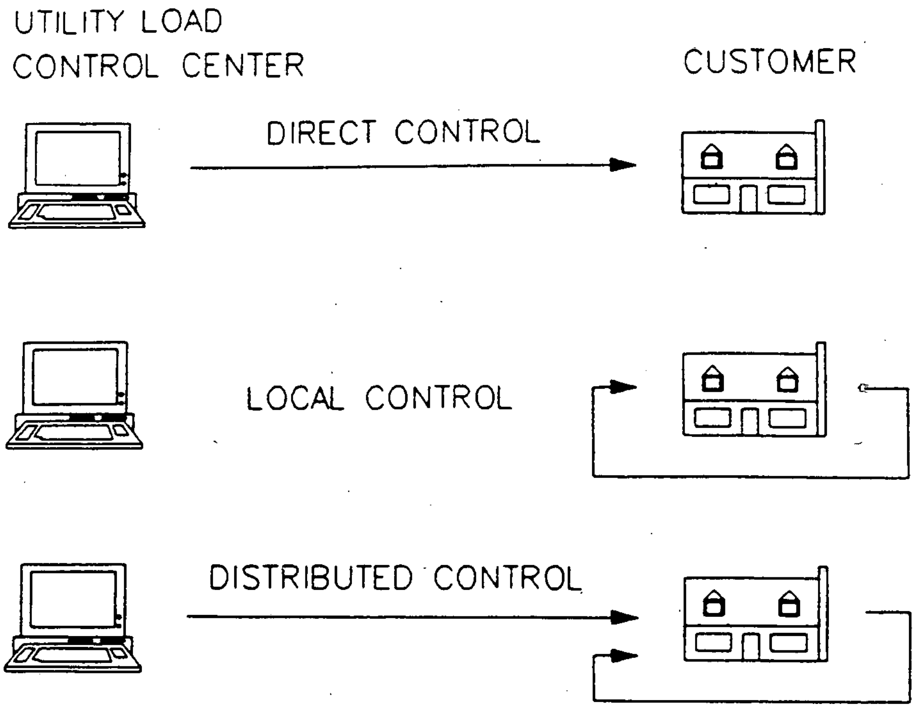

Figure 5. Types of Load Control (Source: EPRI 1990)

Direct load control techniques use a communication system to transmit real-time control commands from the utility to the customer. The utility alone decides the timing and extent of the control actions. The most widely used direct load control technologies are power line carrier (or ripple control system) and radio, which are used to shed remote customer loads (e.g., air conditioning, space heating, and water heating). After the power line carrier was used, utilities found additional applications for its use. One important application is to control the meter time-switches to implement time-of-use rates to encourage consumers to shift their consumption to off-peak hours.

Local load control techniques allow the customer to control their loads, although with some constraints. For example, some utilities install circuit-breakers in residential households, so that power can be interrupted if the consumer exceeds the contracted power. In this case, the consumer can choose which appliances can remain on. In other cases, utilities install interlocking devices that do not allow the connection of several important loads at the same time. Other types of local load controls can save not only power but also energy: for example, timers, thermostats, photocells, and occupancy sensors.

Distributed load control techniques allow control over loads by customers in communication with utilities. For example, the utility may send information, such as prices and requests to reduce demand. Control actions are taken by the smart controller in the customer's premise, based on the utility signals, local conditions, and customer strategies. This type of control is applied mainly to large industrial customers, with whom the utilities have special contracts (e.g., interruptible loads). Distributed load control usually makes use of the telephone lines, a factor that limits the number of customers to be contacted by the utility.

Advanced two-way communication systems can considerably increase the scope of application of distributed load control technologies. Two-way communication will enable automatic and faster interruption of non-essential loads for a large number of customers (potentially all customers), including small consumers. An example of a distributed load control system is described in Appendix B, in which the user programs the HVAC thermostat as a function of the utility rate. If there is an emergency, the load can be shed.

Direct and distributed load control can be used with existing whole building electronic metering equipment to measure the power demand of the controllable load, by measuring the step change in the meter. With distributed load control systems, an override agreement must be made with the consumer to ensure that loads are turned off during special test periods to measure the demand of a particular load.

Direct and distributed load control can also avoid the expense of monitoring a separate control group of customers (EPRI 1988), or avoid the pre-metering effort requirement prior to the installation of conservation measures. If the utility wants to estimate the savings of a particular load control measure, one group of consumers receives the "ON" signal, while the control group receives the "OFF" signal. For some measurements, the same consumer can be in the control group and in the "experimental" group.

7. BUILDING AND HOME AUTOMATION FOR ENERGY MONITORING

7.1 Evolution of Home Automation

The recent advances in communication and metering are being complemented by the progress in the home automation field. Penetration of automation in homes has been evolving through three main activities:

- Development of self-controlled products that are able to regulate their operation (e.g., washing machines and thermostats). During the past two decades, more and more of these products are becoming microprocessor-based ("smart" products), due to performance and flexibility reasons.
- Development of intelligent subsystems in which several smart products communicate among themselves and have a coordinated operating strategy. A possible system would be a system composed of the hot water tank and the appliances that use hot water (dishwasher and washing machine). The dishwasher only turns on when it receives a message from the hot water tank indicating that the water has reached the appropriate temperature.
- Development of home automation systems in which important household appliances (e.g., energy, entertainment, information, and security) have smart controllers and can communicate among themselves. The appliances are operated in an integrated way to provide comfort, convenience, and safety with minimum energy consumption. For example, the same occupancy sensors can be used for lighting control, thermostat set-back operation, and security purposes.

7.2 Home Automation Standards in the United States

Although there is a proliferation of a variety of appliances with microprocessor controls, there has been little success in having the appliances communicate among themselves. This communication problem is primarily due to the lack of widely accepted home automation standards, which is an essential condition for the fast penetration of home automation. In the U.S., industry standards have been developing along three paths: the X-10 system, the Consumer Electronic Bus, and the Smart House.

7.2.1 The X-10 System*

The X-10 system (a de facto industry standard) is a low cost, widely used home automation system that initially used only PLC communication for control of household lighting and appliances. In most cases, the appliances do not have built-in modules; the control modules can be interposed between the the plug and the wall socket, or installed as a built-in replacement for wall switches or sockets. A central controller in the building can remotely control the appliances and receive signals from distributed sensors in the building. The main applications of the X-10 system are for instant or programmed operation of lights and appliances and for security purposes. During the past several years, X-10 introduced infrared, radio, and telephone interfaces to the power line. The X-10 system has been in the market since 1978 and is an open system supported by over 20 manufacturers.

7.2.2 Electronics Industry Association's Consumer Electronic Bus**

The Electronics Industry Association (EIA) has developed the Consumer Electronic Bus (CEBus), an open-standard, multi-media communications protocol and application language. The CEBus standard covers power line, telephone cable (twisted pair cable), coaxial cable, infrared, and low power radio; in the future, the standards may cover optical fiber communication. The protocols are based on the Open System Interconnect (OSI) model (the communication standard defined by the International Standards Organization), used in computer networks and data communication.

A common data rate is used on most media. Audio and video would typically use co-axial cable, whereas telephone and data transmission would typically use twisted pair cable. The CEBus supports two-way communication and has the potential to interconnect all types of appliances in the home, provided they have the proper built-in interface. The CEBus can be used in existing or new homes. Appliance submetering can easily be performed once the appliances are fitted with built-in power transducers.

EIA will monitor the standard, but user groups (e.g., Automated Meter Readers) will be responsible for applying the standard.

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* Information about the X-10 system can be obtained from Peter Lesser, X-10 (USA) Inc., 91 Ruckman Road, Closter, NJ 07624-0420.

** Information about CEBus can be obtained from Tom Mock, Electronics Industry Association, 2001 Pennsylvania Ave., N. W., Washington, D.C., 20006.

7.2.3 The Smart House*

The Smart House project was an initiative of the National Association of Home Builders' Research Foundation and co-sponsored by many utilities and EPRI. The Smart House was based on an integrated network combining power and communication in a single set of conductors, with distributed microprocessors in the network nodes. The network featured special outlets that could only accept authorized appliances. These appliances could communicate among themselves and with the home controller using the same communications protocol.

A demonstration Smart House was built and open to the public in Atlanta, Georgia (*Professional Builder & Remodeler*, 1991). This house featured a user-friendly interactive menu type programming controller, which let the user control the operation of different appliances. Plexus Research developed, under contract from EPRI, the electric utility gateway that allowed the interface between the utility, the metering system, and the Smart House. The gateway allowed remote meter reading of the load profiles of the whole house and of six main appliances (clothes washer, clothes dryer, dishwasher, backup water heater, and two heat pumps).

The base cost for the smart wiring network, smart outlets, and customer controller was around $10,000. Due to the special wiring and outlets requirement, the Smart House concept did not appear to be attractive for retrofitting. For new houses, some consumers may feel discouraged by the large up-front investment that does not include the price of the smart appliances.

The Smart House project has ended. The demonstration home is no longer open to the public, and all non-code equipment has been replaced with code equipment. In addition, the electric utility gateway and the time of use hardware has been taken out of the home. The "smart wiring," automation features, and the heat pump remains in the home. The Edison Electric Institute has no plans to continue the Center for Home Automation, but has started a new project called the "Three E Program" that focuses on energy efficiency, environment, and economic development.

7.3 Use of Home Automation for End-Use Monitoring

Home automation technology is an excellent base to interact with two-way utility communication networks to perform distributed load control with all candidate appliances. Load control can be performed in a customer-friendly way, due to the participation of the consumer in load control. Additionally, since the smart appliances already have the control devices, the utility saves in the cost of the load control units. Additionally, if the appliances have built-in power transducers, end-use metering can be performed

* Information about the Smart House project can be obtained from Mike McGrath, Edison Electric Institute, 701 Pennsylvania Avenue, Washington, D. C. 20004-2696.

inexpensively and in a non-intrusive way. Therefore, there is a need to encourage the development of smart appliances that feature built-in power measurement and control. Distributed load control implies the need for power switching devices in the input stage of the appliance or of its controller. Current sensing can be performed in power switching devices at little extra cost, if any; this already occurs with switching power supplies, where special field effect transistors with built-in current sensing are used (e.g., in computers, where the voltage is kept constant by adjusting the duty cycle of the power transistors in the output stage). Power measurement, calculated by multiplying the current samples by the voltage samples, can be performed by the smart controller provided that it has an analog front-end. Some microcomputer chips (e.g., Intel 8096 and Siemens 80535) already have a multi-channel analog front-end.

Mass production of appliances with built-in power measurement should not carry a large price premium over a smart appliance. A price premium of a few tens of dollars seems likely for the self-metering appliance. Additionally, the built-in power transducer can be used by appliance manufacturers to offer increased features to the consumer (e.g. enhanced self-diagnostics). Utility incentives, similar to those used to encourage the purchase of energy-efficient appliances, can be used to offset the larger cost of self-metering appliances.

8. CONCLUSIONS AND RECOMMENDATIONS

There are a wide variety of techniques that can be used for end-use monitoring, according to data requirements and available budget:

- **Field test equipment** can be used for audits or short-term measurements, due to their portability and ease of installation. However, the availability of equipment to measure field efficiency is limited.
- Currently, **general-purpose data loggers** can be configured to meet a variety of monitoring requirements, connected to suitable transducers. They are compact, reliable, and can be read remotely. Their main drawback is the substantial installation costs and the intrusiveness of the installation and of the equipment itself.
- In applications where loads are constant, **run-time data loggers**, which monitor the status of the loads, may provide an inexpensive solution. Very compact units that are easy to install and battery operated are available; these units are able to integrate the total operating time or count the number of switching cycles.
- **Utility-oriented data loggers**, in addition to the capabilities of general-purpose data loggers, have built-in power transducers and can measure the main variables associated with electricity conversion: demand (kW), reactive power (kVAR), electricity use (kWh), reactive energy (kVARh), and true RMS V and

I. Their installation is simpler and typically more cost-effective than general purpose data loggers, although they suffer from the same, but diminished, drawbacks.

- **Energy management and control systems** (EMCS) are increasingly being used in medium-sized and large buildings. Whole-building data can be disaggregated into end-use consumption using weather dependency of loads, on-site equipment, and operating schedules. The addition of transducers in a building can enhance the operation of EMCS, as well as for end-use monitoring. Constant loads may be estimated by the observed power step change. However, the use of EMCSs for end-use monitoring remains to be developed to its full potential.
- **Two-way communication** appears to be an extremely powerful technology, allowing sophisticated metering, control, and operational and distribution automation activities. Two-way communication is able to meet the most flexible requirements of demand-side management. The use of two-way communication, coupled with smart meters and load controls, can provide high performance end-use metering, besides offering utilities the possibility of implementing sophisticated rate structures and flexible DSM strategies. However, the cost of installing such a system, particularly within an existing infrastructure, needs to be significantly lowered for this type of system to be seriously considered.
- The development of **power line carrier** techniques with capabilities of communication across distribution transformers lowers substantially the installation costs of distributed sensors in large buildings or groups of buildings.
- **Direct and distributed load control** can be used to reduce the costs of metering in programs where is a need for pre-metering or control groups.
- The **Electric ARM and the Load Control Emulator System** use power transducers installed with each appliance, which communicate with the central unit via standard house wiring. Their main drawback is the intrusiveness of the installation and the inconvenience of the equipment protruding in the house.
- The **Non-Intrusive Appliance Load Monitor System** (NIALMS) monitors the whole load at a single point, next to the building meter. The end-use consumption of individual appliances is estimated by analyzing the step changes in power consumption. The NIALMS has not been commercialized. Because it is non-intrusive, fairly accurate, and has a moderate projected cost (around $2,000), it has a high potential for large-scale application in end-use monitoring.

The following activities are needed for advancing the state of the art of monitoring technologies:

- Development of equipment to measure field efficiency of important loads, namely for HVAC systems due to their high potential for savings. The main difficulty is in measuring HVAC process flows with portable transducers with acceptable accuracy. The development of smart, self-calibrating portable sensors to measure water, gas, and air flows with good accuracy is required. The field kits should include software for analysis of the data.
- Development of a low-cost, smart, power transducer, having negligible power consumption and with built-in remote communication capabilities (power line carrier and other).
- Development of self-monitoring appliances to be used with building/home automation (especially needed for commercial and industrial buildings). The use of self-sensing power transistors and enhanced micro-controllers in smart appliances has the potential to achieve that goal with a small incremental cost.
- Development of improved versions of NIALMS to cope with multi-state loads and with continuously varying loads, to be used not only in residences but also in commercial and industrial buildings. The use of harmonic signatures seems to be particularly promising to complement existing pattern recognition algorithms.
- Development of monitoring equipment with comprehensive self-checking and data validation capabilities. Some recent monitoring systems already offer self-checking and diagnostics of the hardware. It is desirable to have systems that can validate the acquired data in real time. The automation of the quality control procedure will save expensive resources to analyze the data, as well as allow earlier detection of existing faults in the measurement system. The error detection, and if possible correction, can be based not only on redundancy (e.g. check-sum procedure), but also on the physics of the process being monitored (e.g., relations between variables, rates of change, and values outside plausible range).
- Development of a user-friendly software package to help users choose the appropriate methodology and technology for end-use monitoring, for a given type of DSM program. The package would include a guide to equipment selection (including models and manufacturers) for each end-use metering function.
- Development of improved methods for analysis and presentation of data. As data overload grows, this problem becomes more urgent.

- Development of improvements in EMCSs, so they will routinely store and archive enough energy data to be useful as monitoring equipment.

Finally, while not the focus of this research project, there are a number of additional research and development activities that are needed for supporting this work on the development of new monitoring technologies:

- Development of an equipment efficiency data base that will contain results from manufacturers and field efficiency tests (including part-load efficiency) for the main types of loads.
- Implementation of the following demonstration projects: (1) end-use monitoring in large buildings (or groups of buildings), using energy management systems or smart meters in conjunction with distributed sensors communicating via a power line carrier; (2) end-use monitoring in houses using two-way communication, smart meters, and load controls; and (3) comprehensive end-use monitoring in houses, using two-way communication and home automation, and using an open standard (CEBus).
- Training of skilled personnel for monitoring activities. With the growth of DSM programs, there is a need to develop staff training programs with suitable preparation to carry out performance measurement. Technical support materials on the experimental and methodological aspects of demand-side evaluation will also be needed.
- Establishment of an independent test laboratory, for measuring power consumption and efficiency, comparing nameplate data to measured data, and for gathering technology related information (e.g., measure lifetime). The creation of such a laboratory might result in the avoidance, or reduction, in end-use metering costs. The information collected by this laboratory would then be distributed to consumers, utilities, government agencies, and private companies.

The high cost of end-use metering equipment is a chicken and egg situation. The equipment is expensive because it is not sold in large quantities; because it is expensive, utilities carry out few end-use metering activities, thereby reducing the demand and market for such equipment. Utilities can take a decisive role in reducing the cost of end-use metering equipment by placing large orders and creating a more competitive market for monitoring equipment. Similarly, the regulatory community may decide to require utilities to conduct end-use monitoring or provide financial and non-monetary incentives to these companies to implement such an activity.

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APPENDIX A

GLOSSARY

Active power: This quantity, also called real power, is the energy delivered to the load per unit of time. The active power is measured in Watts (W) or in multiples of this unit such as kW, MW, and GW. (*See power factor.*)

Analog front-end: The subsystem in a data acquisition system which receives the analog inputs (inputs changing continuously, such as temperatures, currents, and voltages), carries out signal conditioning (filtering and amplification), and converts them into digital values (binary strings of zeroes and ones). **Multi-channel analog front-ends** have more than one channel (normally powers of 2 such as 4, 8, 16, 32, 64, ...). **Integrated analog front-ends** feature the different parts of the subsystem built in a single integrated circuit.

Analog-to-digital converters: An electronic unit that converts an analog electric signal into a digital value. The accuracy of conversion is measured by the number of bits that typically can be 8, 10, 12, 14, and 16. (*See analog front-end.*)

Automatic breaker reclosure: Most of the faults in an electric power system are transient. When a fault occurs in a given point, the breakers surrounding that point open to isolate the fault. Automatic breaker reclosure re-establishes the supply to the loads, after a small time period to let the transient fault to disappear.

Automatic reclosures: *See automatic breaker reclosure.*

Capacitor: An electrical device made by sandwiching an insulating layer between two conductive layers, which are the device terminals. Capacitors are used by utilities for power factor compensation and filters. (*See power factor.*)

Capacitor bank switching: The capacitors are normally grouped in banks that are switched on or off according to the need to compensate the power factor. (*See capacitor and power factor.*)

CEBus: The Consumer Electronic Bus (CEBus) is a multi-media communications protocol being developed for home automation applications by the Electronics Industry Association. This open-standard will allow appliances and devices made by different manufacturers to communicate among themselves in an integrated fashion.

Chart recorder: A device used to register graphically the changes of a certain variable (e.g., temperature, humidity, and power). Typically, the recording is made by moving a pen on graphical paper that is moving perpendicularly to the pen's movement.

Cluster meter: A group of meters for different loads (or consumers) which are located in the same room or panel, in order to make meter reading more efficient, or to save space.

Cluster-type meter wiring: Wiring of meters in a cluster configuration. (*See cluster meter.*)

Communication and control cards: The subsystem used to exchange data and control commands with the outside world.

Conductors: The physical devices used to carry electrical power or signals. Conductors can take the form of cables (insulated copper or aluminum wires) or overhead lines.

Control relay: A relay used to switch loads on and off. (*See relay.*)

Controller: A device used to command the operation of loads.

Smart controller: A controller with built-in "intelligence," given by a programmable microcomputer that can react to changes in the operating environment, communicate with other controllers, and perform time-scheduled operations.

Current transformer: A device used to measure electrical current, composed of a magnetic core and a copper coil wound on the core. The conductor carrying the unknown current is placed on the hole of the core. In a **clamp-on current transformer,** the magnetic core can be opened by applying hand pressure on the device, allowing the current-carrying conductor to be inserted in the hole. Measurements are made with the magnetic core closed. Clamp-on type units are intended for temporary measurements. In **split-core transformers**, the magnetic core is divided into two halves held together by a fixing device. Split-core units are normally used for permanent measurement applications.

Daisy-chained: An electrical connection between several electronic systems in which each device receives the signals from a previous system in the chain and passes the signals to the next system down the chain.

Data acquisition boards: Electronic boards that can be connected to a computer (either through the computer bus or through the parallel/serial interfaces), featuring an analog front-end able to convert and read analog and digital signals.

Data logger: A device used to acquire time-varying signals. The information can be stored in several ways ranging from graphical plots to computer memory.

Distribution: An electrical power system is composed of generation, transmission, and distribution. The distribution subsystem is the low voltage part of the network which supplies the different consumers.

Distribution automation: In the electrical distribution network, there are several functions (such as protection, optimal network configuration, voltage regulation, power factor compensation, and event recording) that have to be sent as fast as possible to achieve maximum reliability and minimum operating costs. Distribution automation is the implementation of those functions in an automated way, that is without the intervention of an operator.

Distribution transformers: Devices used to lower the voltage level from the medium voltage to the low voltage (110-120 Volts) used by consumers.

Duty cycle: When a device operates in a periodic and intermittent fashion, the duty cycle is the percentage of time when the device is "ON".

EEROM: EEROM stands for electrically-erasable read-only memory, a type of non-volatile semiconductor memory, where both writing and reading the information is achieved by applying electrical pulses. The information can be erased and modified, byte by byte.

EPROM: EPROM stands for erasable programmable read-only memory, a type of high-density non-volatile (even when the power is cut-off) semiconductor memory. The information is written by applying electric pulses and is erased by exposing the memories to ultra-violet light. In this case, all the information is erased.

Electronic modules: Devices, typically made with small electronic boards, that can be used to expand/enhance the capabilities of an electronic system. A typical example is the IBM-PC that can receive several electronic modules connected to its BUS, allowing a wide variety of functions to be implemented.

Event recording: The registration and collection of data related to pre-defined types of occurrences. These can be related to abnormal situations (e.g., a surge in the voltage level) or normal operating conditions (e.g., recording the switching times of a particular piece of equipment).

Frequency: *See Hz.*

Global load: This refers to all of the loads in a given location.

Harmonics: Electrical signals with frequencies that are integral multiples of the fundamental frequency. For example, in a 60 Hz application, a 120 Hz component is called the second harmonic. (*See Hz.*)

Harmonic signatures: Some loads produce harmonics, which are different according to the load type. The harmonic signature of the load is the shape of the current waveform, which is influenced by harmonics produced by the load and which can be used to identify the type of load.

Harmonic-tuned filter: This component is designed to select and extract a particular harmonic from a current or voltage signal.

Higher order harmonics: Harmonics with higher frequencies. (*See harmonics.*)

Hybrid type meter: An electricity meter along with an optical sensor that produces a pulse for each turn of the disk. The pulses are collected and processed by an electronic module.

Hz: Hz is the abbreviation for Hertz, the unit used to measure frequency (rate of oscillation of alternating current). One Hz is equal to one cycle per second.

I: The symbol used to represent electrical current.

Inductance: The property of an electrical device or circuit by virtue of which a varying current induces an electromotive force in that circuit, thereby resisting the change.

Instantaneous power: The rate of energy delivered at a given moment, which is equal to the product of the instantaneous current times the instantaneous voltage.

Integrated Signal Digital Network (ISDN): A wideband network being introduced in most countries and able to carry data, digital voice, and images at high rates of transmission. It is expected that ISDN will be available in most households during the first quarter of the 21st century.

Interrogate: To collect data from a data acquisition system (DAS), or to inquire about the status of a DAS.

Interruptible loads: Loads that can be switched off to decrease peak demand.

kVA (kilovolt-amperes): Unit of apparent power. The product of the voltage (in volts) and current (in amperes) values in an electrical circuit, divided by one thousand. In DC circuits, equal to the kW flowing. In AC circuits, the kVA is equal to the kW if the power factor is equal to one; otherwise the kVA is higher than the kW. (*See power factor.*)

kVARh: Unit of reactive energy. (*See reactive energy and power factor.*)

LCD: This abbreviation stands for liquid-crystal displays, widely used in portable instrumentation due to their low power consumption.

Load control channel: Some meters and data collection equipment have available outputs that can switch loads on and off (either directly or through an interposed relay).

Low frequency line carrier: *See power line carrier.*

Magnetic mass storage: This type of memory includes hard-disks, magnetic tapes, and diskettes. It features high-density, but requires moving parts and is much slower than semiconductor memory.

Mercury-wetted relay: A relay in which the switching contacts are wetted in mercury and are enclosed in a glass bubble. This type of configuration decreases the wear on the contacts, providing a large number of switching operations before failure. (*See relay.*)

Meter time switches: Devices in meters which allow the implementation of time-of-use rates. (*See real-time prices.*)

Microprocessor: A digital circuit, featuring arithmetic and logic reasoning capabilities, whose operation is defined by a set of instructions (called the program).

Multi-state appliance: Most appliances are on-off appliances (i.e., two-state appliances). Other appliances, such as defrosting refrigerators, ranges, dimming lights, and variable speed controls, have more than two operating states and, therefore, are called multi-state appliances.

Multiplexers: A device with multiple input channels and a single output channel, in which only one of the input channels is connected at a time with the output. The selection of the input channel is made through the address control lines of the multiplexer.

Neutral-to-ground communication: This type of power line carrier communication system uses the neutral and ground wires for communication. (*See power line carrier.*)

Non-volatile semiconductor memory: A type of electronic memory without moving parts, which is able to retain the information stored, even when the power is disconnected. (*See EEROM, EPROM, and semiconductor memory.*)

Open system: A system whose design conforms with widely accepted standards in terms of expansion (by connection of additional modules), communication interfaces, and software. The use of open systems and standards allows the use and connection of pieces of equipment made by different manufacturers.

Optical encoder: A device used to monitor the position of a moving part (either a shaft or a linear rod). The device has a light emitter (typically, a light emitting diode) in which the motion interrupts the beam of light focused on an optical detector, resulting in the emission of electrical pulses.

Optical port: This is an optical communication interface typically consisting of an optical plug, containing both a light emitter and a light detector, and allowing bi-directional digital communication.

Opto-isolation: The transmission of information by transforming an electrical signal to an optical signal and the other way round. When a signal is converted to an optical signal (typically, using a light-emitting diode), transmitted through a transparent medium (glass, plastic, or air) and converted back to an electrical signal by an optical detector (typically, a photo-diode or a phototransistor), opto-isolation is achieved.

Opto-isolated digital outputs: Output channels that are opto-isolated from the monitoring and control system. (*See opto-isolation.*)

Pattern recognition algorithm: A method of identification based on the analysis of the shape of a time varying signal.

Phase: The indication of the type of power supply for which the equipment is designed. The two main categories are single phase and three phase (sometimes referred to as polyphase).

Phase angle: Angular displacement between two voltages or between a current and a voltage.

Phase meter: A measuring device that measures the angular displacement between two waveforms with the same frequency.

Phase symmetry: In a symmetric three-phase system, the three voltages are equal in magnitude and displaced by 120 degrees.

Power analyzer: A measuring and monitoring device able to measure voltages, currents, power factor, reactive power, energy, reactive energy, and sometimes harmonics.

Power factor: The ratio between the real power (measured in Watts or kW) and apparent power (the product of the voltage times the current measured in Volt-amperes or kVA). Power factor is expressed either as a decimal fraction (from zero to one) or a percentage (0 to 100%). In the case of pure sinusoidal waveforms (i.e. not distorted by harmonics), the power factor is equal to the cosine of the phase angle between the voltage and current waves in an AC circuit. This value is known as the "displacement" power factor (since it deals with the displacement in time between the voltage and current). Since cosine values range from 0 to 1, the apparent power is always greater than or equal to the real power. If the power factor is less than 1, more current is required to deliver a unit of real power at a certain voltage, than if the power factor were 1. In the case of waveforms that include harmonics, the harmonic current adds to the total current without contributing to the real power, so the power factor is reduced. Many power electronic devices (such as ASDs) have high displacement power factors (over 90%) but overall power factors that are significantly lower depending on design and operating conditions. This higher current is undesirable because the energy lost to heat in the wires supplying power is proportional to the square of the current. In motors and other inductive loads operating in AC circuits, the current wave lags behind the voltage wave. When a capacitive load is applied to an AC circuit, the voltage wave lags behind the current wave. Since these are opposite effects, they can be used to cancel each other. Thus capacitors can be (and very commonly are) used to correct the poor (low) power factor. In DC circuits, the power factor is always 1.

Power factor compensation: *See power factor.*

PLC: *See power line carrier.*

Power line carrier (PLC): The power lines (either 50 or 60 Hz) can be used to transmit digital information by superimposing higher frequencies on the power line. These frequencies can run from a few hundred Hz (ripple control) to over 100 kHz. (*See Hz.*)

Power meter: A device that measures power. (*See active power and instantaneous power.*)

Proprietary network: A network owned and operated by a single company.

Pulse initiating capabilities: *See pulse initiating meter.*

Pulse initiating circuit: A circuit that produces a pulse for each unit measured. (*See pulse initiating meter.*)

Pulse initiating meter: An integrating meter (electricity, gas, water, etc.) that produces an electrical pulse for each unit measured. In some meters, the measured amount required to produce a pulse can be adjusted.

RAM: Random Access Memory (RAM) is the most widely used type of semiconductor memory in computer-based equipment. These memories can be read and written in a very fast way and are relatively inexpensive. Their weak point for data collection is that they are volatile, that is they require a power source to keep the data (i.e., data will be lost when power is disconnected).

RMS: This abbreviation stands for root mean square of a periodic variable. For currents or voltages, the RMS value of these variables would produce the same power in a resistive load, as the time-changing currents or voltages. **True RMS** is the same as measured RMS, and is not the same as equipment specifications.

Reactive energy: The energy flow in the network due to the presence of inductances and capacitances. This energy flow is due to the energy storage in those inductances and capacitances. Although the net value of this energy flow is zero, the total current is increased due to the reactive energy, causing higher losses and the derating of the power network. The units used to measure the reactive energy are the VARh and its multiples. When the load is predominantly inductive, the current is lagging in relation to the voltage, and the reactive energy absorbed is designated **lagging kVARhs.** On the contrary, if the load is capacitive, the current leads the voltage, and the reactive energy supplied is called **leading kVARhs.** (*See power factor*).

Reactive power: The rate of reactive energy flow in the network. The units to measure the apparent power are the VAR and its multiples. (*See reactive energy and power factor.*)

Real power: *See active power.*

Real-time price: The price of the electricity supply changes constantly due to changes in the generation mix. These changes are required to be able to meet the demand that is varying all of the time. The real-time price of electricity reflects the instantaneous real cost of electricity, and although its use would improve overall economic efficiency, it has not been applied due to the need of applying meters with computing and communication capabilities. (*See smart meters.*)

Recording register: A device that stores information (pulses) in a digital format.

Relay: A device used to control the operation of switching contacts. A control coil energized by a small current is used to produce the motion of the switching contacts that can carry larger currents.

Ripple control: *See power line carrier.*

Rotating disk kWh meters: This is the conventional type of electricity meter, also called the Ferraris meter, in which there is a rotating disk whose speed is proportional to the power being delivered. The revolutions are counted by a mechanical or an electronic system, to totalize the energy delivered. There are similar meters available to measure the reactive energy (kVARh).

Rotating meters: Rotating disk kWh meters.

Sectionalizing isolator control: The operation of isolating a portion of the power network. When there is a fault, or it is necessary to carry out maintenance in a certain area of the network, it is necessary to isolate that part of the network. This is done by opening switches (the isolators), conveniently distributed in the network.

Semiconductor memory: This is an electronic memory made with silicon integrated circuits, featuring high density and no moving parts. (*See EEROM, EPROM, and RAM.*)

Serial interface: A type of computer communication interface in which the information is sent sequentially in time (serial format).

Signal conditioning: The procedure to filter, amplify, or scale analog signals, in order to remove unwanted information and to match the sensitivity of the data collection equipment.

Signal processing: This is an operation normally done by microprocessors or other digital signal processors, to extract information contained in the signals, including pattern recognition. (*See pattern recognition.*)

Smart meter: A microcomputer-based electricity meter featuring computing and communication capabilities. These type of meters can work with time-varying tariffs (in particular, with real-time tariffs), can be read remotely, and can control several loads. (*See real-time prices.*)

Step change: A sudden change between two operating states of a system.

Step transitions: *See step change.*

Tariff: The energy rate that the consumer has to pay. The rate may be a function of the time of day and the time of year (**time-differentiated tariffs**). These tariffs may also include demand charges and penalties for the reactive energy consumed. Tariffs may reflect the constantly changing generation cost, either fully or in a mitigated way (**dynamic tariffs**). (*See real-time pricing, power factor, and reactive energy.*)

Transceiver: A device that can act as a receiver and as a transmitter of information.

Transducer: A device (sensor) used to convert a physical variable into another signal of either similar or different physical nature. The transducers used for energy monitoring applications normally convert different types of signals (temperature, flow, current, power, illumination, etc.) into electrical signals that can be read by data monitoring equipment. In **pulse emitting transducers**, transformers conver measured signals into a sequence of pulses. In **built-in or external power transducers**, output is a linear function of real power. In **watt-hour transducers**, measured energy use is integrated over a period of time.

Transformer: In its most common form, a device to increase or decrease the voltage in an AC system. The primary side of the transformer is connected to the source of power; the secondary side, to the load. A step-down transformer (the most-common type in transmission and distribution systems) reduces the primary voltage to the secondary voltage. A step-up transformer (used for example at power plants to increase the generation voltage to the transmission voltage) increases the primary voltage to the secondary voltage.

Transient: An event of short duration, when there are abrupt changes in the currents or the voltages, normally associated with switching of loads from one operating state to another. Some transients are associated with power outages and lightning storms.

Transient signature: The variation in time of the current, voltage, or power, when there is a transient (*See transient*). In particular, when a load changes its operating state, the current, voltage, or power waveforms can identify the type of load that has been operated.

Transient waveform: *See transient signature.*

Transponder: A communication node that can both receive and send information in a communicative network.

Two-way communication system: A communication system in which there is a bi-directional flow of information. The consumer premises can receive information and controls from the utility and can also be interrogated.

V: Symbol for Volt, the unit used for measuring voltage. (*See voltage.*)

Voltage: The difference in electrical potential between two points. In a three-phase system, two types of voltages may be defined: (1) **line-to-line voltage** is the electrical potential difference between any two phases; and (2) **line-to-ground voltage** is the voltage between a phase and the ground. The line-to-line voltage is about 80% larger than the line-to-ground voltage.

Wire systems: In a three-phase system, the wiring can assume one of two configurations: (1) **3-wire systems** (in which each conductor carries the phase current) are used for symmetrical three phase loads (there is no need for a return conductor, as the 3-phase currents sum to zero); (2) **4-wire systems**, which has the three wires mentioned above as well as a neutral return conductor. The 4-wire system is required when there are single-phase loads. In a properly designed system, with a similar amount of loads in each phase, the current in the neutral return conductor is almost zero.

APPENDIX B

MONITORING EQUIPMENT EXAMPLES

In this appendix, illustrative examples of monitoring equipment and systems are presented. Before reviewing these examples, the authors would like to repeat some of the caveats mentioned in the main text. First, this project was of limited budget and duration. Accordingly, the report did not cover all technologies, equipment (e.g., BTU meters and portable flow meters), and manufacturers. We encourage readers to examine another report for a more comprehensive and detailed review of some of these products, which was prepared for the Electric Power Research Institute, Bonneville Power Administration, and the Center for Electric End-Use Data (Abbott et al. 1992). Second, the mention of specific products, vendors, or firms does not represent an endorsement by CIEE or Lawrence Berkeley Laboratory. Third, end-use monitoring technology is changing quickly, so that what we know today is surely to be quite different in the near future in terms of equipment costs and capabilities, and levels of accuracy. And fourth, equipment cost can vary quite significantly, depending on the quantity of equipment purchased. Where available, we provide cost/unit for single-unit purchases and for bulk purchases.

The section heading for each type of equipment refers to the sections (chapters or sub-chapters) used in the main report. However, we do not provide examples for all sections of the main report.

2.3 Run-Time Data Loggers

2.3.1 TimeFrame System™ *

The TimeFrame System is a 32 channel real-time, universal, analog recording device. Any of the 32 channels can be configured to 20ma signal, pulse outputs, voltage, amperage, true power wattage, or power factor. Sensors are polled continuously and can be programmed to record in intervals of 1 minute recording to 99 minutes. Depending on configuration, TimeFrame has 256 kBytes of memory capacity and a built-in modem. Continuous 24V loop power can be applied by the unit to any sensors.

TimeFrame current sensors are available 5, 20, 50, 100, 200, 400, 800, and 1600 amp sizes and come standard in solid core design. Split core options are available. TimeFrame voltage sensors are available in 120/208V and 277/480V configurations. Additional sensors up to 4130 volts can be custom ordered. Wattage is determined by a multiplication of volts, amps and power factor. Single and multi-phase readings are possible.

Using the 20ma signal configuration, most commercially available sensors including temperature, pressure, humidity, and flow can be correlated to energy usage. In addition, many 20ma sensors are available to monitor natural gas and pollutants.

Data are stored on board and are transmitted via built-in modem to a central data collection computer. TimeFrame's central computer program operates on a desktop personal computer and controls data acquisition, scheduling, site configuration, and report generation. The central

* Information on the TimeFrame system can be obtained from Jim Halpern, Measuring and Monitoring Services, Inc., 2 Broad Street, Red Bank, NJ 17701.

program comes with many pre-configured reports, and is also capable of generating export files in standard spreadsheet and data base formats for analysis by external programs.

For monitoring lighting systems and motor run time, a digital-only version of the system is available with 32 channels capable of recording on/off status in real time. This unit can determine the status by use of light sensing photo cells, current transducers, or voltage sensors.

The analog model is available at $1,100 and the digital model is available at $875. Most analog sensors are $88, and most digital sensors are $17. Various configurations of the Central Station program are available and start at $2,500.

2.3.2 SmartLoggers™ *

Pacific Science and Technology makes SmartLoggers™ to monitor lights, motors, water heaters, heat pumps, air conditioners, fans, and other electrical devices. SmartLoggers can be installed quickly without an electrician because they require no hard wiring and are small and light weight.

The Time-of-Use™ (TOU) SmartLoggers monitor the actual time when electrical devices are turned on and off. This information allows the user to answer peak impact questions, create load shapes, provide operations feedback to end users, verify savings, and calculate energy consumption. The TOU SmartLoggers come in three models: Lighting ($380), Motor ($395), and CT ($448). All models use a special cable and software to retrieve, analyze, and graph the data or export it to the user's analysis software.

The Run-Time Calculator™ (RTC) SmartLoggers measure the run-time of various electrical devices. Multiplying the monitored run-time by the power draw gives you the energy use. The RTC SmartLoggers can be used for energy audits, run-time surveys, maintenance scheduling, and other projects and come in three models: Lighting ($120), Motor ($139), and CT ($195). All models can either count the total number of operating hours or the number of on/off cycles.

Lighting Loggers™ use a built-in photocell and can be fastened to light fixtures by a magnetic strip attached on the top of the logger or by using velcro, tape, or other fasteners. Motor Loggers™ are placed on or near a monitored device and operate by sensing the stray magnetic field. The CT Loggers™ have a current transformer that clips over the monitored wire to detect the current draw of an electrical device.

Plug Loggers™ sense the current in the wire leading to lights, appliances, or any other electrical devices that are plugged into an outlet. They are available in TOU ($420) and RTC ($149) loggers and can be used as an alternative to the Lighting Loggers or Motor Loggers when monitoring at an electrical outlet is preferable. Flow Loggers™ are available in TOU ($455) and RTC ($205) versions and use an in-line flow switch to sense fluid flow. These loggers can be used to monitor shower water or other liquid flows.

Occupancy Loggers™ ($195) are a combination of an occupancy sensor and either an RTC or TOU Lighting Logger. This monitoring tool records the time the lights are left on when no one is in the room, allowing the user to calculate by direct measurement the potential energy savings of installing an occupancy sensor.

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* Information on the SmartLoggers can be obtained from David Greenwood, Pacific Science & Technology Company, 64 NW Franklin Ave., Bend, OR 97701.

Power Loggers™ ($995) are four channel true-power data loggers intended for single three-phase loads such as motors, drives, and heat pumps or multiple single-phase loads. In addition, the Power Logger has analog channels that permit measurement of other parameters such as temperature.

2.3.3 MyTech totalizers*

This family of totalizers has a light unit ($122) and a current transformer unit ($193) for general-purpose use, with similar performance as the ones described above. Another unit ($452) combines a light and an occupancy sensor, and measures the number of operating hours of lighting in unoccupied areas. This unit can be used to estimate the savings that can be achieved with occupancy sensors.

5.2. Smart Meters

5.2.1 METRICOM Meters**

METRICOM has developed solid-state meters that sample the voltage and current waveforms at 16 samples per cycle, in order to perform instantaneous calculation of the following variables: voltage (both line-to-line and line-to-ground), current, active power (Watts), reactive power (VARs), power factor, energy (kWhs), and reactive energy (kVARhs). The minimum and maximum values of these quantities, as well as the time of occurrence, are stored. The meter can be programmed to register the readings at intervals ranging from 1 minute to one day.

Single-phase meters cost $325, whereas three-phase meters cost up to $695. For an additional $25, the meters can record gas consumption, using a pulse initiating device (such as a magnetic or an optical encoder). This device is especially useful for utilities that sell electricity and gas. Meter programming (for time-of-use rates or for data collection) and meter reading can be done with a portable terminal via the optical port on the front of the unit, or remotely via a radio/power line carrier communication system.

METRICOM's two-way communication system is an hybrid UHF radio/power line carrier system, whose diagram is shown in Figure A.1. The utility control and data collection center sends commands and requests for data to satellite microcomputer-based units, via the utility's communication network (microwave, cable, or fiber optics). The satellite units communicate via a UHF packet communication network, the Wide Area Network (WAN), with radio transceivers located in the secondary of the distribution transformers. All one-way commands can be verified by a receipt message.

The radio transceivers communicate with the smart meters, load control units, and distribution automation devices via a Local Area Network (LAN) implemented with a power line carrier. In suburban areas, one transceiver typically serves eight residential customers. In urban areas, the ratio can vary from 1:5 to 1:25 (condominium) depending on the number of customers connected

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* Information on MyTech measurement and monitoring equipment can be obtained from Dan Daneff, My Tech, 706 Brentwood St., Austin, TX 78752.

** Information can be obtained from George Wren, METRICOM Inc., 980 University Avenue, Los Gatos, CA 95030.

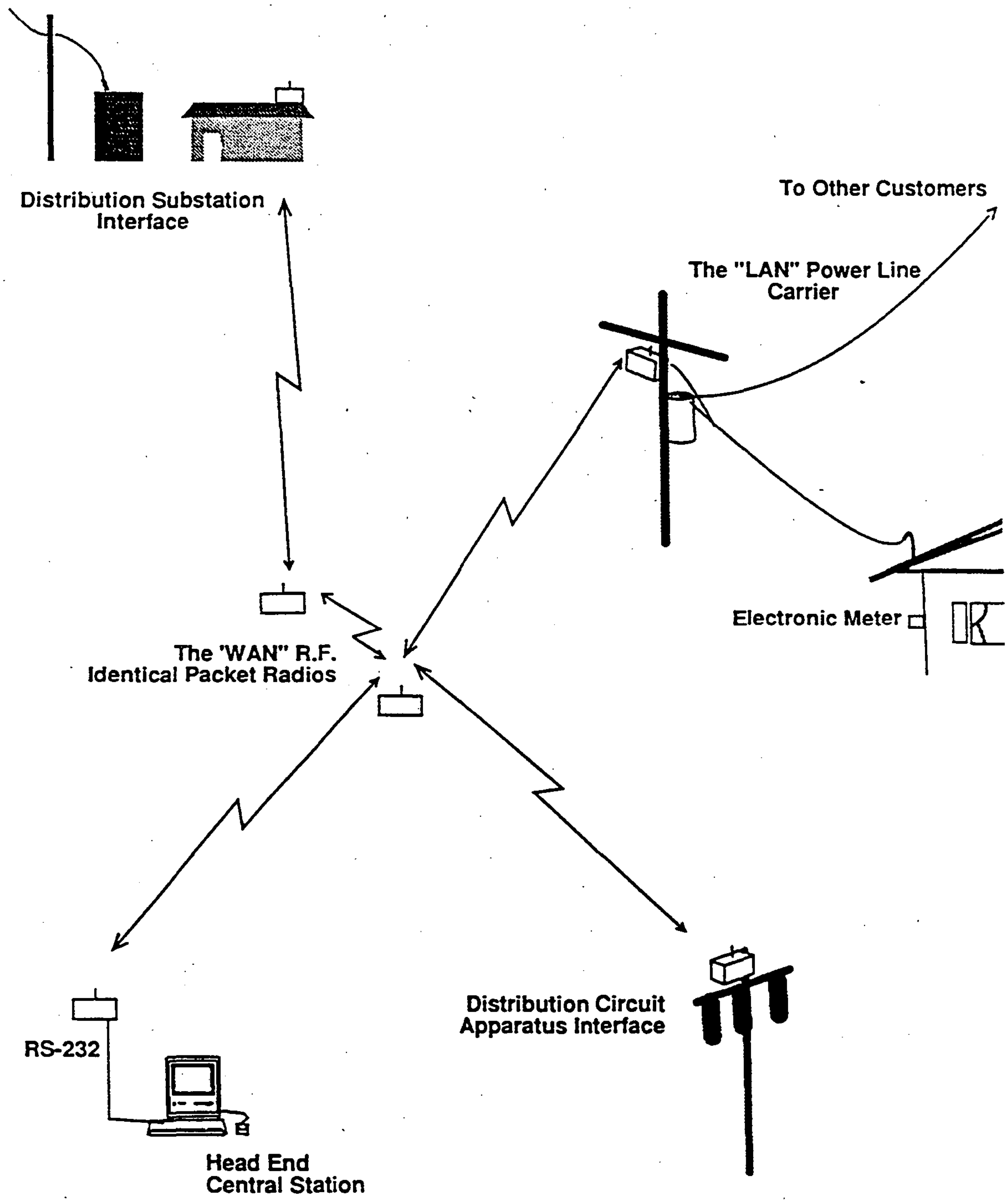

Figure A.1. Radio/Power Line Carrier Communication System (Source: Metricom) to a single transformer. The cost of the transceivers is around $1,000.

METRICOM has installed several thousand electronic meters and the associated communication network in Southern California Edison's (SCE) territory and Pacific Gas & Electric's (PG&E) territory. In some cases, the two-way communication system has been used for distribution automation functions (remote voltage monitoring, monitoring and control of automatic reclosers, and capacitor bank switching).

METRICOM can also supply a Load Control Unit that receives commands via a power line carrier from the radio transceiver. The control unit can be used by the utility to perform load management. The control unit has three channels, one with a 240 V - 20 A relay (to control large appliances) and two 120 V - 3 A relays. These outputs can control small/medium appliances or, with an interposing relay, large appliances. The control unit costs $225.

The meter and load control unit can also be used to monitor the power consumption of single loads by switching the control channel associated with that load. In order to extract the on/off load profiles, the control unit would require status inputs for reading the operating status of the appliance.

5.2.2 Domestic Automation Company's Meters*

The Domestic Automation Company (DAC) is developing a two-way communication system for distribution automation load management and metering, similar to the system developed by METRICOM. CellNet™ uses a digital cellular radio wide area network and spread spectrum radio local area network. CellNet employs an open system architecture, built on industry standards. This enables the system to interface with a variety of vendor products, such as meters and existing utility software application packages.

DAC's system uses radio, along with the following subsystems:

- The System Controller (located in the utility control center and implemented with a powerful computer) is at the top of the hierarchical control structure. The System Controller communicates with the lower level, the Cell Master Units, via a leased phone line or microwave. The System Controller is a standards-based network of UNIX workstations that manages CellNet.
- The Cell Master Units use a UHF radio (952 MHz outbound channel and 928 MHz inbound channel) located and powered next to the distribution transformers. The radio units cover an area with a 3 to 5 mile radius. These transceivers communicate via a radio with the meters, load controls, and data monitoring equipment associated with the consumers.

* Information on DAC equipment can be obtained from Tom Nicotre, Domestic Automation Company, 75 Shoreway Road, San Carlos, CA 94070.

5.2.3 Integrated Communication System's TranstexT*

Integrated Communication System's (ICS) TranstexT, developed in the mid-1980s with the support of the Southern Company, has targeted energy management and control information services. The initial TranstexT development system used the television as the display unit and a touch-tone phone for input. That interactive system provided entertainment, banking/shopping transactions and communications, besides home energy management. The system could implement time-of-use rates (the utility was able to send a real-time peak rate), remote meter reading, and distributed load control, after taking into account the customer's appliance settings.

The new TranstexT system currently on the market is directed only to energy management functions and was developed in conjunction with Johnson Controls, The Southern Company, American Electric Power, and Asea-Brown Boveri. The current TranstexT system contains the following components:

- The System Manager (a computer and software located at the utility) sends commands and receives data from customers via telephone lines. The System Manager sends prices and related information to the consumer, and receives load profile and meter data from the consumer.
- The Com'set 2000 is connected to both the customer's phone and house wiring. Communication inside the house is via a power line carrier. Currently, communication between the home and the utility is over the existing phone network. The System can also be designed to work with proprietary utility networks.
- The thermostat, with an LCD display and keypad, allows the user to program the time of use and temperature settings of the appliances (e.g., HVAC system and water heating) as a function of four possible rates. The thermostat and controller are compatible with almost all HVAC systems. The thermostat acts as a terminal for the consumer, displaying the price of electricity, the electricity consumed by price tier, and the projected bill. The customer can also interrogate the system through the thermostat to find out the projected electricity bill under standard fixed rates.
- The controller, a microprocessor-based unit, operates the appliances in accordance with the programmed instructions of the consumer. The controller operates the loads based on the customer's programmed comfort desires at various times and prices. For example, the water heater is switched on only when the rates are cheaper and when the consumer needs hot water; otherwise, only when necessary.
- Control relays for large and small appliances: a large control relay can be used for switching on and off the 240 V water heater. Up to eight small relay units (such as the low-cost, BSR, X-10 or Radio Shack units) can be used to operate small appliances.

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* Information about the TranstexT system can be obtained from Tom Parker, Integrated Communication Systems, Inc., 5000 Highlands Parkway, Suite 170, Smyrna, GA 30082.

- The hybrid type meter (a Poly Phase version of ABB's state of the art Alpha Electronic Meter) measures electricity consumption at different price levels and communicates via a power line carrier with the modem, allowing remote metering by the utility. The meter can store up to 40 days of load data, recorded at 15-minute intervals.

Around 1,000 units have been installed by the American Electric Power Company, the Gulf Power Company, and the Pacific Gas & Electric Company. The installed cost of the TranstexT system ranges from $1,600 to $1,700 per home when purchased in quantities of a few hundred units in the pilot studies. However, for larger manufacturing quantities, the price is projected at $700 per home.

5.2.4 Quadlogic Controls Corporation's Transmeter*

Quadlogic Controls Corporation has developed an advanced technology for power line carrier communication (the Transmeter) which has the following main features: (1) use of neutral-to-ground communication, (2) auto-selection (the unit automatically tries different communication frequencies and automatically selects the frequency which gives the best signal-to-noise ratio), through an adaptive process of the optimal carrier frequency, and (3) capability of signal transmission between the low voltage and the medium voltage of the distribution transformers (this is a conventional limitation in power line carrier communication systems).** This power line carrier-based system has been used with several types of meters made by Quadlogic, in hundreds of commercial buildings and condominiums, for submetering and remote meter reading of each unit of the building.

The Transmeter is a microprocessor-based meter that measures peak demand and energy and has non-volatile data recording capabilities. This meter has several inputs (e.g., for reading the temperature or water consumption) and optional load control capabilities. This meter can perform time-of-use metering, either fixed or externally triggered rates. The meter has a digital display to allow reading by the customer, and costs from $300 to $600, depending on the number of phases and options.

Typically, a large number of Transmeters are linked to and read by the Communications Interface Processor (CIP), normally located in the building's electric switchboard room, which is a microcomputer-controlled power line carrier and telephone modem communication system. The CIP sends metered data through the telephone line to a central billing and data processing center.

In DSM evaluation projects, the Transmeter can be used for end-use monitoring of single pieces of equipment or for loads located in different parts of a building. Additionally, the meter can be used for energy monitoring in a multi-building complex (e.g., a university campus) to evaluate the performance of individual buildings or of loads on those buildings. The Transmeter can also be used with a central EMCS for monitoring and control (e.g., Madison Square Garden

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* Information on the Quadlogic meters can be obtained from Doron Shafrir, Quadlogic Controls Corporation, 520 Broadway, Sixth Floor, New York, NY 10012.

** The transformers normally block or strongly attenuate the transmission of power line carrier signals. This problem can be overcome by capacitive coupling, by using lower frequencies or by amplifying the signals with a tuned amplifier.

in New York City).

Quadlogic also makes the miniCLOSET, a cluster meter that is mounted in the distribution panel of the building and that can be connected to 48 current transformers. This meter is used in buildings with cluster-type meter wiring used to meter individual tenants. The miniCLOSET can also be used for end-use monitoring of different loads in a commercial building, provided the measurements can be taken at the same location (typically, the distribution panel).

Quadlogic also makes a residential direct load control (DLC) unit, a potentially useful device for end-use metering. This unit was developed for controlling peak demand and metering of room air-conditioners in New York City. The DLC unit is normally mailed to customers, who install the unit between the appliance plug and the wall socket. The unit can be remotely controlled by radio, and the unit registers the load profile as well as the status of the connection of the unit to the appliance and to the wall plug. The participants in the program are provided an incentive by the utility. The DLC unit (with or without load control capabilities) can be used in a non-intrusive way, since the customer is responsible for installing the unit. The unit can be used to measure the performance of individual appliances in either residences or commercial buildings. The cost of the unit is $500, and several thousand units have been field tested.

5.2.5 Credit and Load Management System (CALMS)*

The Credit and Load Management System (CALMS) was developed in England in the mid-1980s by the South Eastern Electricity Board. CALMS is similar in concept and operation to the more recent version of Transtext. The control modules for the main appliances can be adjusted by the consumer to operate only below a certain electricity cost level. Besides the two-way communication link supported by telephone and power line carrier, the electricity prices can be broadcasted. CALMS can also be used for other value-added services (e.g., gas and water meter reading, home security, and sprinkler control).

Field trials involving several hundred customers were successfully carried out in England. Although utility privatization delayed the dissemination of this technology, a 100,000 homes project is now under consideration.

* Information about CALMS can be obtained from Robert Peddie, Torness, The Mount Drive, Reigate, Surrey RH2 OEZ, United Kingdom.

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