FEATURE ARTICLE

Residential Energy Monitoring and Computerized Surveillance via Utility Power Flows

George W. Hart

The common law has always recognized a man's home as his castle, impregnable,...
—S. D. Warren and L. D. Brandeis

Abstract — **All new technologies have the potential to affect society in a complex manner, with both beneficial and detrimental consequences. The author considers an illustrative case study: a nonintrusive appliance load monitoring technique that can provide vital information to help avoid future energy crises, but can also be used for surveillance purposes. There appears to be a significant potential for the technology to be abused. The danger that the technology might eventually lead to an erosion of civil liberties and privacy rights leaves its developers in an ethical quandary. How should this technology be controlled?**

At one point in Woody Allen's futuristic comedy *Sleeper,* he and his revolutionary associates are discovered by government forces who monitor an increase in "the power function" where they are working. [1] This type of automated discovery based on electric power usage is now technically possible and could become commonplace in the near future.

A novel *Nonintrusive Appliance Load Monitor* has been designed to aid electric utilities in the collection of appliance end use data. [2,3] This device is installed at the revenue-meter socket of a residence (see Fig. 1) and, by using sophisticated signal analysis techniques on the voltage and current waveforms, determines the nature and exact usage characteristics of the individual appliances within the home which constitute the load. The monitor requires only the information externally available from measurements of the load; no entry into the home is necessary to place sensors on separate appliances or branch circuits; no appliance survey or other cooperation from the residents is required.

A key feature of this new technique is its nonintrusive nature. The device can alternatively be installed on a utility pole at a distance from the site it is monitoring. With this mounting scheme, not even a momentary loss of electrical service is necessary for installation. From this unseen and unsuspected vantage point, the monitor has a view deep into the workings of the residence. After observing the residence for a short while, it generates a list of objects (appliances) and events (usages) that the occupants may consider completely private.

The intended use of the device is completely benign. Utilities have important legitimate needs for end use load data. Previously available data collection methods are expensive and clumsy compared to the nonintrusive technique, so it is natural for utility load researchers to welcome more sophisticated tools for instrumentation and data collection. The load monitor is currently being packaged into the form of a commercial product, and initial interest from utilities suggests that tens of thousands may be installed within the first five years of manufacture.

For the scientist or engineer developing the nonintrusive load monitor, however, its development, promulgation, and commercialization present a rather interesting case study of the ethical issues that can accompany new technologies. It is a powerful example within a larger trend: Modern developments within communication theory, detection and estimation theory, signal processing, and microprocessor-based computation are continually presenting new applications for recognizing patterns or extracting signals and information out of noise, which can be used for surveillance purposes. Miniature video cameras, night-vision devices, infrared detectors, and motion detectors are just a few examples of the technology of "the new surveillance". [4]

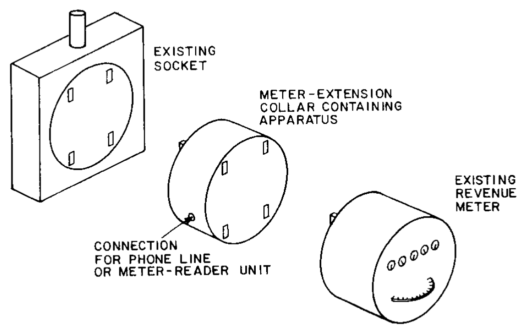

Fig. 1. The nonintrusive appliance load monitor is contained within an "extension collar," which mounts quickly and easily between the utility kilowatt-hour meter and its socket.

The nonintrusive appliance load monitor is a particularly worrisome entrant into this category as it penetrates directly into the private residence, perhaps the last bastion of privacy as civil liberties gradually erode away. [5] By raising these issues at this time and presenting the load monitor in this forum, I can hope to limit this technology to appropriate applications and prevent it from becoming an Orwellian "Big Brother."

THE TECHNOLOGY

The nonintrusive appliance load monitor was designed to allow convenient, inexpensive determination of the energy consumption characteristics of major residential electrical appliances. (It has further applications to commercial and industrial loads.) Energy usage characteristics as a function of time and ambient temperature are important data for a variety of purposes in

The author is with the Department of Electrical Engineering and Center for Telecommunications Research, Columbia University, New York, New York.

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modern energy-intensive societies. Laboratory measurements of appliance energy consumption are not useful as most appliance characteristics are strongly user-dependent.

Typically, large U.S. utilities collect detailed energy consumption measurements on dozens to hundreds of homes and compile this into a database used by their research departments. Existing instrumentation requires that sensors be installed on individual appliances and branch circuits within the home. Runs of sensor wiring (or, in some systems, power-line carrier techniques within the house wiring) are used to bring the data to a data collection device within the home. The recorded data is periodically picked up by utility personnel, or, in some systems, transmitted to a central computer facility via telephone.

The intrusiveness of these existing techniques has disadvantages beyond the obvious time, cost, inconvenience, and damage associated with appliance surveys, sensor installation, data collection, sensor maintenance, and eventual sensor removal. Utilities assume certain financial liabilities when their equipment is installed. Also, they must return to modify their instrumentation as the appliance inventory changes (assuming they are informed of this by the residents). Because of the limited number of people willing to accept utility intrusion, the sample may be skewed toward energy-conscious homeowners. In addition, there is always a danger that the reminding presence of energy monitoring instrumentation may cause the residents to unconsciously modify their energy consumption habits. Finally, most existing systems are restricted to a small number of data channels, which limits the number of appliances that can be monitored at each site.

The nonintrusive technique was designed to eliminate these difficulties by approaching the load monitoring problem from a fresh point of view. The power wiring is modeled as a communication channel, and the power flows into the home are treated as signals to be analyzed for their information content. Instead of bringing sensors to the individual appliances, the aggregate load is disaggregated by signal analysis and pattern recognition techniques implemented in software.

The key idea is that changes in the on/off state of an appliance within the residence can be detected by step changes in the total power consumption that is measured outside the house. For example, if a house contains a hair drier that consumes 1000 W and 25 VAR, then a step change of that characteristic size occurs every time it is turned on, and its negative occurs when it is turned off. The activity of other appliances is associated with other characteristic changes in real and reactive power. The power change step sizes for the appliances monitored at one field site are shown in Fig. 2. These regions of the complex power plane were determined by using cluster analysis techniques on the set of observed step changes in the total house load.

Once the clustering indicated by the ellipses in Fig. 2 is carried out, the set of cluster regions together form a "code table" for interpreting further step changes. Appliances are treated as transmitters, and step changes are effectively treated as messages transmitted by the appliances, so the load monitor is designed to act as an adaptive receiver.

By tabulating statistics on the distribution of on-times and off-times, the nature of the appliances within a residence may be identified without recourse to an appliance survey. This provides the labels on Fig. 2. A number of straightforward technical details, omitted here but discussed in [2,3], are required in the "receiver" to accommodate certain realities of residential "transmissions," such as simultaneous messages

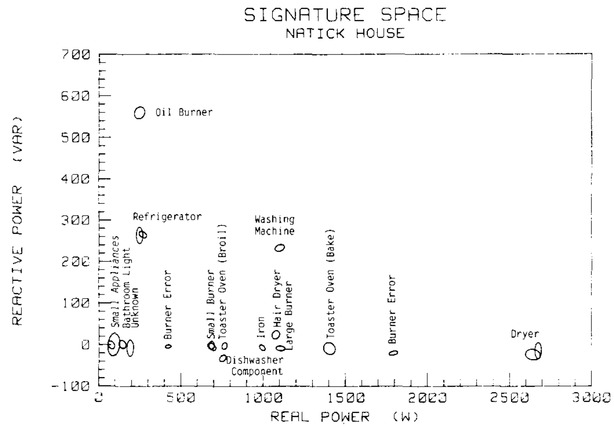

Fig. 2. Regions of the complex power plane associated with the appliances identified in one field test of the nonintrusive appliance load monitor. Step changes are easily detected in the total load and compared to the figure to see which appliance changed state.

from more than one appliance, the three-terminal nature of residential wiring, transient currents at appliance turn-on, and changes in measured power that are due only to utility line-voltage variations.

In order to ascertain the appliance class, or "consumer's name," of an appliance, "duty cycles" are examined in addition to power consumption levels. For example, as a consequence of the economics of high-power switching devices, the illusion of continuously variable burners on an electric stove is accomplished with "pulse-duration modulation," in which the burner is actually turned fully on and fully off periodically, for periods on the order of seconds. In contrast, thermostats on ovens result in duty cycles on the order of minutes. By tabulating the sample duty cycle statistics, devices with similar operating power levels are often easily distinguished.

A prototype has been tested in three homes with excellent results. Table I lists the appliances identified in these field tests. Weaknesses in the initial algorithm resulted in only 75 percent to 90 percent of the on/off events of these appliances being reported; however, the technology is still in its developmental infancy, having only been born in 1984. A second-generation

TABLE I

List of Appliances Identified and Monitored in Tests of the Prototype Nonintrusive Appliance Load Monitor at Three Field Sites

Refrigerator	Dishwasher
Bar Refrigerator	Toaster Oven
Freezer	Hair Drier
Ice Maker	Water Bed
Oven	Hot Tub Pump
Large Burner on Stove	Basement Lights
Small Burner	Kitchen Light
Oil Burner	Food Processor
Iron	Water Pump
Bathroom Light	Hot Water Heater
Washing Machine	Dehumidifier
Drier	Garage Door Openers

prototype that attempts to remedy the problems is currently being tested, and initial results are much superior. Results for a typical appliance (150 W incandescent lighting) are shown in Fig. 3.

Additional research is in progress for understanding how to deal with complex appliances, such as dishwashers and washing machines, with a number of distinct components and operating power levels (rather than one component and only two states: off and on). [6] Certain classes of appliances cannot be monitored by this nonintrusive technique, such as low power and continuously-variable power appliances, and appliances that are never switched on or off. However, these are not significant limitations for utility load research purposes.

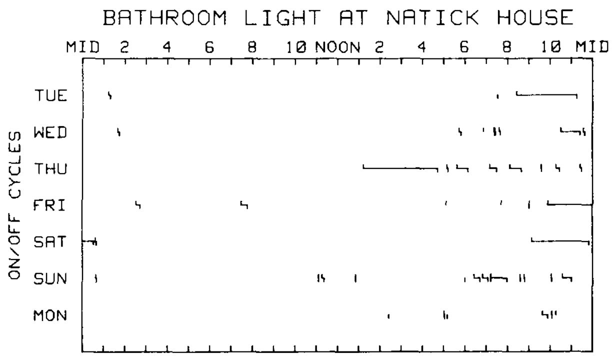

Fig. 3. Bathroom light activity during one week of nonintrusive monitoring. Horizontal bars indicate times for which the load monitor reported the light on. Vertical ticks above the bars indicate turn-on events and ticks below the bars indicate turn-off events. Unmatched on or off events reveal errors of the algorithm.

INTENDED USES OF THE TECHNOLOGY

The purpose of the nonintrusive appliance load monitor is to collect data for load research purposes from a statistical sample of homes whose occupants are informed of its presence and the nature of the data being collected. The data is to be tagged in a manner that does not identify the occupants, and averaged or otherwise combined with data from other homes in the sample.

Statistically averaged appliance end use data is valuable to several audiences. Utilities are directly interested in load forecasting (on time scales ranging from hours to decades) to assure future generation, transmission, and distribution capacity. They are also interested in understanding the economic effects of alternative rate schedules, such as the discounts available in many areas for energy consumed in electric water heating. Collection of appliance performance data is also mandated by public utility commissions, as it is essential to policy makers for evaluating energy conservation options such as (1) research, development and commercialization of advanced appliance technologies, (2) consumer education concerning energy consumption and life cycle costs, (3) federal and state-regulated appliance efficiency standards, and (4) utility rebates favoring efficient models. [7] Appliance manufacturers also have an interest in understanding how their products are typically operated in the field.

Some energy-conscious individuals would be very interested in detailed data for their own energy consumption if it were conveniently and inexpensively available. The nonintrusive appliance load monitor could be installed temporarily at the resident's request. This would result in a detailed "energy audit" which would help them understand their energy usage and suggest ways of reducing their monthly bills. Services of this type could be provided either by the regional utility or by third parties.

Another use for the technology is to locate and identify device failures which might be evidenced by unusual power consumption or duty cycle characteristics. In one of the three field tests of the prototype, a failed underground septic pump was detected by its abnormally low power consumption. The home owner was unaware of the failure because the associated alarm had also malfunctioned. Presumably, if the house had not been monitored the situation would have persisted until the backup pump failed, with unpleasant consequences.

ADDITIONAL USES OF THE TECHNOLOGY

In addition to the intended uses already described, there are many other purposes to which the nonintrusive load monitoring technology could be applied. These additional applications raise many questions concerning civil liberties in general and the privacy of the home in particular. I am genuinely afraid of the possible effects this technology might have on society, as the following scenario is all too easy to imagine: Initially a few houses are monitored for data collection purposes. Gradually, more and more houses are monitored, perhaps for billing purposes, such as water heater discounts. Eventually, all homes are monitored and a variety of surveillance and control applications become routine.

The details visible in Fig. 3 give only a hint of the information content of power flows for surveillance purposes. It is easy to tell when someone is in the shower, for example, based on the use of a water pump, water heater, bathroom light, and/or hair drier. In one field test, for example, I was not entirely sure of my interpretation of the output until the residents confirmed what the plots indicated—that one occupant did routinely take noontime showers. In another home, one could easily determine when the bed in the master bedroom was made and when it was uncovered! The bed was a water bed, and its electric heater cycled on for shorter periods when the blankets were in place to insulate it.

Many surveillance scenarios suggest themselves. Power flow-based surveillance could be used by law enforcement agencies to monitor the activities of suspected criminals or political opposition. For example, the use of a printing press by a reputed counterfeiter or a dissident could easily be detected. Certain illegal objects can also be detected through their use, e.g., in countries where photocopiers are controlled, nonintrusive methods could be used to locate them. Occupant surveillance for illegal purposes could take many forms. As one example, a sophisticated burglar might conceivably use power monitoring to identify the movements of occupants, e.g., to time his break-in during a period when the occupant is away or showering. As a final surveillance application, I would be surprised if nonintrusive load monitoring were not long known to government agencies for monitoring foreign embassies on their soil, but I have no evidence on this point.

As a tool for detecting classes of objects, one can imagine a "junk mail" scenario: In an effort to reduce rates by finding additional sources of income, utility companies could sell advertisers and salespeople mailing lists of consumers lacking assorted consumer appliances.

DISCUSSION

Clearly, many moral and legal questions concerning privacy and civil liberties are raised by the nonintrusive load monitoring technology. One fundamental question is what rights do energy consumers have over their power flows? Who can monitor them, and after they are monitored, who owns the data, and who controls it? Who is responsible for its accuracy and the consequences of those errors which inevitably arise? Should the data collection hardware be restricted to only certain organizations? To what extent are the caretakers of the data responsible for unauthorized access to it by others? These issues are not particular to this application, of course; they apply to the privacy of all computerized data banks in any free society [8,9] and lead one to further consider the essential nature of privacy itself. [10]

Note that the "solution" of utilities requiring "informed consent" of those being monitored is not sufficient, and not only because unauthorized nonutility uses *will* occur. A typical energy consumer would not understand the wealth of detail that can be extracted from the signals continually being transmitted *out* of the home over the power lines. Informed citizenry who understand that the system might be recording their every movement including such details as when their beds are made and when they are uncovered are not likely to give consent.

Although utility managers certainly have no interest in offending their customers by wantonly revealing personal information, how would they respond to requests from law enforcement agencies seeking to verify or disprove the alibis of suspects living in monitored homes? Can load monitors be installed to gather information on suspected criminals? Are existing wiretap laws relevant? Does any regulation prevent police, private investigators, or other nonutility parties from monitoring the power flows of others?

Although I am not a lawyer, my understanding is that U.S. citizens have very little legal or constitutional privacy protection that could apply in this context. The U.S. Constitution does not explicitly mention any right to privacy. Wiretap laws apparently do not apply as they are specifically restricted to signals intended as *messages* or *communications*. [11] Finally, common-law rights to privacy do not appear relevant: "The courts had not held that individuals could invoke the common-law right to prevent the recording of personal information about themselves by a governmental agency or private organization". [9] Given that the U.S. Supreme Court has recently ruled that personal and private household trash deposited for curbside refuse collection is neither personal nor private [12], there appears to be little hope for a judicial ruling limiting power line monitoring.

There are many ways in which official surveillance might gradually instill itself through load monitoring technology. Could certain energy consuming acts be specially taxed, for example, as energy supplies become inadequate? One can imagine a new policy option in which certain appliance activities, say air conditioning during peak utility demand hours, might be highly taxed in order to encourage load reduction. Certain objects, such as outdated "energy guzzling" refrigerators, could also be located and reported in the name of the general good. Another scenario would allow "salubrity taxes" on appliance usage judged harmful — television watching suggests itself. Gradually, many other regulations could be enforced through load monitoring.

The use of nonintrusive monitoring to enforce laws is particularly disturbing because it constitutes what has been termed "routinized discovery". [13] Discovery techniques (e.g., computer matching of records from different government data banks) merge the traditional two-step process of first detecting an offence, and then seeking an offender. Instead, the crime and criminal are identified simultaneously. Critics of automatic discovery procedures argue that this violates U.S. constitutional guarantees of "due process of law" as it shifts the burden of proof onto the accused to show that no crime occurred, rather than following the maxim of "innocent until proven guilty." Furthermore, it is claimed that suspects lose the right to face their accuser, as it is a nameless computer program which makes the accusations.

For those interested in protecting their own privacy, the monitor can be rendered almost useless by "communications jamming" techniques which mask the actual power flows. Charging and discharging an energy storage device to create random step functions at short random intervals will defeat the monitor. However, this is detectable in itself and will indicate something to those doing the monitoring. One can easily imagine an escalation of measures and countermeasures taking place here. However, the most unsatisfactory aspect of readily available countermeasures is that the first people to install them are probably those one would least like to have them, e.g., the counterfeiter seeking to obviate a court-ordered monitor to detect his printing press.

SOME REACTIONS OF SCIENTISTS AND ENGINEERS

For those interested in the case study of how the nonintrusive appliance load monitor technology is being received, I can report on the reactions of a small sample of scientists and engineers with whom I have discussed the matter. Almost without exception, these technically oriented people do not see any danger in this technology and are not concerned with its possible evolution into a surveillance technology. The immediate reaction of most engineers is to suggest technical solutions to the technical problems. For example, data security can be improved with password protection on data banks or cryptographic techniques. The identification error rate can be lowered with various improvements to the hardware and software. From the privacy advocate's point of view, jamming is an available solution. When pressed concerning the issue, many scientists and engineers seem to accept that all technology will be abused, but consider it outside of their purview to act to prevent it. Some have gone as far as to suggest that a discussion of these issues is inappropriate for a technical report presenting the technology.

Another reaction is to minimize the importance of this particular case by pointing out that tapping power lines is no worse than tapping phone lines. As this presumably occurs everyday without any fundamental collapse of society, we have little to fear from tapped power lines, it is claimed.

CONCLUSIONS

As my views differ from many of my peers on these matters, I have chosen to present the technology in a context that emphasizes the complexity of the issues. Every technology with socially useful applications also has undesirable applications. It has been observed that the many new surveillance technologies were all developed for other, socially useful, purposes, but then were quickly adapted to surveillance as soon as they became available. [8] The degree to which the developers of a technology are responsible for its unforeseen applications is debatable, but clearly everyone is obliged to be concerned with the foreseeable consequences of their actions. Publishing the details of a method which will almost certainly be used in many injurious, though unintended, ways is an action with foreseeable consequences.

I expect this situation is not uncommon among scientists and engineers. An interesting problem arises in their area of expertise, containing solid technical content, and with a large potential value to society. Furthermore, this value is recognized to the extent that they receive the necessary support and funding to do the required work. Yet, there is a concern for the long-term consequences of the research. Once published, the ideas will follow their own courses, in large part independently of the control of the originators, and there is a certain feeling of helplessness.

The only direct control available to the creators is suppression of the ideas. This is somewhat drastic since the beneficial applications are also lost, and in any case it is most likely a temporary solution at best. The deliberate concealment of technical advances has usually been considered anathema to the progress of society. This is in fact the justification for our elaborate patent systems. However, the argument has been made very persuasively that quantitative and qualitative changes in the way science now affects society compel us to consider the case for more restraint in research and dissemination. [14] The enormous scale of modern industry and the synthetic nature of modern science combine to release new substances (e.g., fluorocarbons and DDT), new life forms, and new technological systems (e.g., computerized data banks and load monitors) on unprecedented scales, in short time periods, with unforeseen consequences on our physical and social environment. It is not clear that we can continue to rely on the implicit presumption that the environment will respond to all new forces merely by finding a slightly perturbed equilibrium point. At some point, the restorative capacity of any system will be exceeded.

In the case of the nonintrusive appliance load monitor, the option to suppress is now moot, as the ideas are already in circulation, so alternative methods of controlling the technology must be sought. Specifically, I recommend that legal restrictions be enacted or clarified so that electric power usage is considered as private as any phone conversation. Load research should require the informed written consent of the monitored parties. Load monitoring for purposes other than for load research should be prohibited, except that perhaps governmental surveillance may be permitted under a search warrant. The load monitoring equipment itself should be controlled so that it is not available for general use. Until such laws appear, electric utilities and load monitor manufacturers should enact their own voluntary guidelines to the same effect (although this wouldn't restrict a "private investigator" from assembling his own load monitor in his basement and installing it as desired).

Only time will tell if this particular technology actually has any effect at all, good or bad, upon society. In the meantime, scientists and engineers are obliged to consider the possible consequences, weigh them, and make a judgment call. My feeling in this case is that the technology is appropriate for its purpose and can be kept in rein if we are vigilant. However, it is a troubling enough case that I know others will feel differently; I encourage discussion and welcome feedback.

Dedicated to the memory of the late Professor Fred C. Schweppe. I am grateful to Gary Marx for helpful discussions.

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