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Electricity load decomposition prototype for household appliances: System Design and Development

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Abstract

The growing interest in green building is driving the development of energy efficiency building models. One of the essential elements is an effective and efficient Energy Management system. Traditionally, the system contains lots of meters measuring each appliance. Non-Intrusive Load Monitoring (NILM) is a technique for estimating power consumption of each appliance by disaggregating the end-use power consumption measured by a single meter. However, existing NILM are facing two main problems: 1) some of the small appliances and the similar appliances cannot have their power consumption estimated, and 2) NILM requires a long learning process, which means that a new learning process might be needed if a new appliance is connected. To tackle these problems, this paper proposes to use Intrusive Signature (IS) and Power Line Communication (PLC) for circuit-level load decomposition. The paper focuses on the development of a device using frequency domain signature as the IS. The prototype is developed and deployed on the circuit. The results show an accuracy between 83% to 93%.

Keywords: Electricity Decomposition; Intrusive Signature; Circuit Level; Power Line Communication; Small Appliance

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1. Introduction

Energy crisis and global warming are among the most severe problem in our generation. Building sector, as one of the largest sectors of greenhouse gases emission, uses about 30% is electricity in the U.S, which accounts about 2061 million tons of CO^2 equivalent [1]. Electricity management is one of the main focuses of green building. In the LEED version 4 [2], the smart grid becomes a vital rating factor, encouraging occupants to install electricity meters to monitor the detailed electricity consumption to provide decision making assistants for building performance's improvement. Therefore, an effective electricity management system would be a future trend of the green building development. NILM, also called electricity disaggregation, is an approach to estimate the individual electricity consumption of individual appliances in a household by disaggregating the total power consumption data. As only a household-level meter is required, the energy monitoring becomes more economical and convenient. Therefore, it would be an ideal electricity management system providing a useful but economical solution.

Compared to a total value of power consumption in the electricity bill, the details of individual power consumption for each appliance are helpful for the user to monitor and reduce their power usage. Although the idea of NILM was first proposed 30 years ago, there is still a lack of reliable commercial products because NILM requires complex models, algorithm, and software to process and analysis the data. One main reason is that the accuracy of NILM still has much room for improvement and the deployment process is costly and time-consuming.

The objective of this paper is to develop a prototype of an IS-based load decomposition device. It is expected to optimize the accuracy of NILM by eliminating the numbers of combinations of appliance status. Moreover, they can also improve the Automatic-Setup process of NILM by providing a signal to inform the system that a new appliance is installed and instruct the system to learn the new signature of the appliance.

2. Related Works

Non-intrusive load monitoring was first proposed by Hart from the Massachusetts Institute of Technology [3]. The researchers in NILM mainly focus on two types of approaches: appliance signature and energy disaggregation algorithm. Hart only briefly described what kinds of factors are possible for signature learning without providing the detailed techniques[3]. According to a survey [4], the signature development is mature and can show what kinds of data should be measured and how to use it for appliance detection, especially for the rapid growth of transient states signature. Form the survey [5], the framework of signature systems are similar to the one proposed in 2012. There is less research conducted in the non-traditional signature field. Moreover, there lacks research in Intrusive Signature. Therefore, it is still a new approach in NILM area even that Hart proposed the basic idea of Intrusive signature in 1992. Hart divided the IS into two categories: Physical Intrusive Signature and Electrically Intrusive Signature. Physical Intrusive Signature is generated by a physical intrusion ("tag") attached to the appliance. It generates a signal when the appliance operates, in the form of a radio frequency signal or a certain current harmonic. Electrical Intrusive Signature also generates the electrical signature, but by the utility interface. The system works like a radar or sonar, the signal is sent to the load and the "echo" come out is estimated for the type of appliance. However, the utilities would not support it due to interference and power quality.

The electricity disaggregation algorithm is evolving rapidly in the last thirty years. Different algorithms have been developed and achieved high accuracy. Initially, Hart's algorithm is based on the Expectation-Maximization (EM) algorithm, which treats the problem as a combinatorial optimization problem. Later, researchers [6–8] adopt other algorithms, including Support Vector Machine, Naive Bayes classifier, Hidden Markov model, Neural Network and k-nearest neighbors. However, there exists no single algorithm, which can detect all types of appliances. Compared to the Non-Intrusive Signature development, the Intrusive Signature development is slow. For the future development of Intrusive Signature, it would be similar to the steady-state signature that uses the low sampling frequency meter for measuring. Because of the commercialization of NILM, the low-frequency meter provides an enormous advantage in economics due to the small setup and maintenance cost. The feature of intrusive signatures is controllable, as the signature would be distinct enough. Therefore, the original types of steady-state signature, changing real power and reactive power, can be adopted. Compared to other signatures, the intrusive signature is simple and easy to be detected, indicating that a straightforward detection program is required and the simple circuit can generate the signature. The cost of the IS tag and strip can be significantly low. The proposed algorithm is a useful reference for operation program of IS Tag and Strip. Since the Intrusive Signature is distinct, the proposing algorithm can already detect most of the Intrusive Signal. Relatively, the disaggregate algorithm such as HMM are sophisticated and not suitable for operation program because that algorithm requires extensive manual setup. For the distinct signature, this kind of the algorithm would cause substantial potential waste of time and resource to process unnecessary and sophisticated algorithm.

3. Methodology

3.1. Framework

The prototype of the load decomposition system comprises of two parts: the load monitoring and transmission component at the strip; and the data receiving/processing unit connected to the computer. The workflow of the system is shown in figure 1: When any appliance connected on the strip has a state changed, the current is measured, and the data is sent to the Microcontroller Unit (MCU); the MCU will decode the measurement and transmit the measurement to the PLC module. The PLC module is in charge of transmitting the data over the powerline to the data receiving/processing unit, which sends the received data to the computer for data processing. The load decomposition program on the computer will process the data to estimate which appliance on the strip has a state change. To implement the function of the prototype, the load decomposition algorithm and hardware design will be briefly described in the next two subsections.

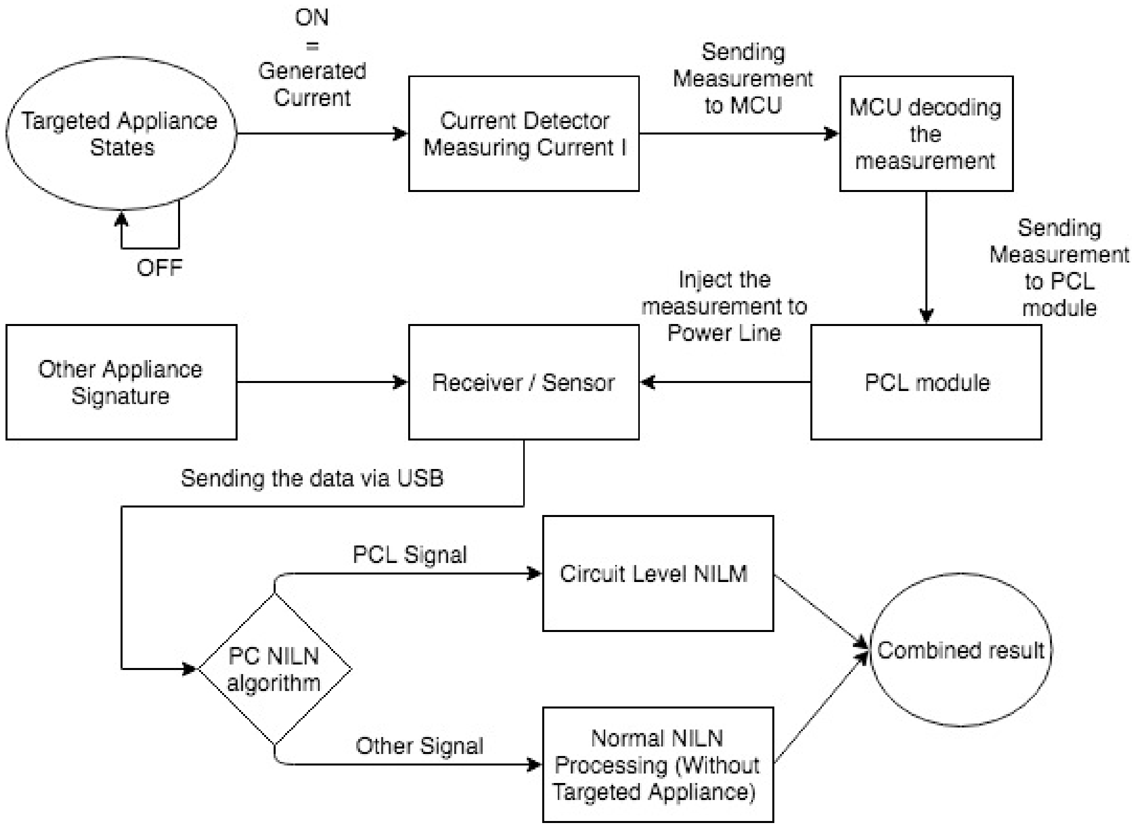

Fig. 1. Workflow of the Prototype

3.2. Load Decomposition Algorithm

Before running the load decomposition algorithm, a database was built for the small appliance which might be connected to the strip (For demonstration purpose in this study, the authors collected the data for the fan, phone charger, hair dryer, electric kettle and LED light). The current, voltage, real power and reactive power of the appliances were measured at 1Hz using the C.A. 8230 power analyzer manufactured by Chauvin Arnoux. The authors performed a series of state change events on the appliance and recorded the difference between the post-event and pre-event measurements. K-means clustering was used for all the measurement changes into clusters. In this way, the appliance state-change signature was constructed.

In the working situation of the prototype, as power consumption data was measured at 1Hz, and the difference between any two neighboring seconds was calculated. The EM algorithm is used to match the measured difference with the recorded signature in the pre-defined database. In this way, the appliance with state change can be identified through the algorithm. The decomposition algorithm was implemented using MATLAB.

3.3. Hardware Design

An Intrusive Signature Tag (IS Tag) was developed. The fundamental of IS Strip is combined load decomposition and PLC technique to achieve the circuit-level load decomposition. The main component in the system comprises MCU, HL-PLC module, transformer and current meter module. The circuit of the load monitoring and transmission component at the strip is shown in figure 2. The actual appearances of the load monitoring and transmission component, and the data receiving/processing unit are shown in figure 3.

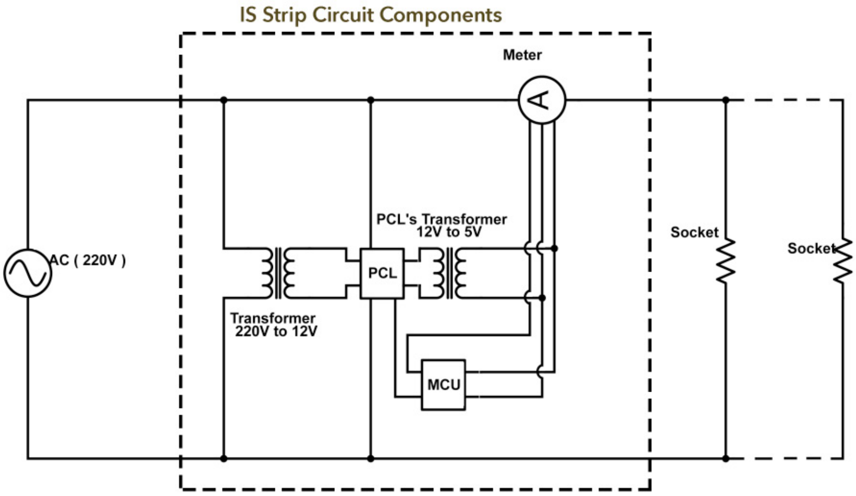

Fig. 2. Circuit Design of the IS Strip

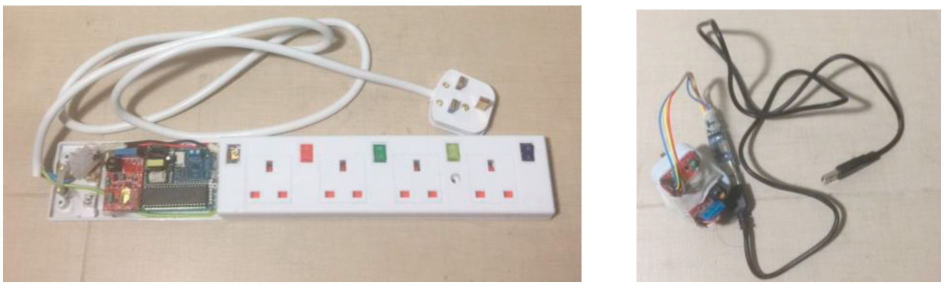

Fig. 3. The appearance of the Prototype for a) IS Strip; and b) IS Strip Receiver

4. Evaluation of the Prototype's Performance

As the load decomposition is mainly determined by the accuracy of event detection of the state change of the appliances, the accuracy of event detection is validated for the developed prototype with adopted decomposition algorithm. The appliances connected to the prototype include two types of appliances: 1) appliances with ON/OFF states: LED light, electric kettle, and phone charger; 2) appliances with finite states: fan and hairdryer. Two experiments are conducted: 1) a single appliance is connected to the prototype at a time for ten times and the decomposition program was run for 3 minutes each time; 2) two appliances are connected to the prototypes at a time for ten times, and the decomposition program was run for 3 minutes each time. Random state changes were conducted in each experiment. Each state change (timestamp, event, and the corresponding appliance) was recorded as the ground truth. The state changes estimated by the prototype were compared with the ground truth. Event detection accuracy, event classification accuracy, and overall accuracy are used as the performance metrics for the prototype, as defined in equation (1) to (3).

$$Event\ Detection\ Accuracy = \frac{\#\ of\ correctly\ classified\ events}{\#\ of\ correctly\ detected\ events + \#\ of\ falsely\ detected\ events} \quad (1)$$

$$Event\ Classification\ Accuracy = \frac{\#\ of\ correctly\ classified\ events}{\#\ of\ correctly\ detected\ events} \quad (2)$$

$$Overall\ Accuracy = \frac{\#\ of\ correctly\ classified\ events}{\#\ of\ true\ events} \quad (3)$$

The results of both experiments are summarized in table 1. Table 1 shows that the IS Strip system works well when only one appliance is connected to the prototype. The performance degraded when one more appliance is connected to the prototype. The performance of the prototype will degrade when more appliance is connected to the prototype.

Table 1. Performance of the prototype in two experiments

	Single Appliance connected	Two Appliance connected
Detection Accuracy (%)	93.62	78.43
Classification Accuracy (%)	96.56	87.25
Overall Accuracy (%)	92.64	83.33

4. Conclusions

NILM was proposed more than 20 years, but it is still not commercialized due to disadvantages, e.g., its set up process takes a long time, results are inaccurate, and it requires expensive devices (e.g., electricity meter with a high sampling rate). Intrusive signature is one possible alternative, which has not attracted many research interests in the past decades. This paper shows that it is feasible to use low-cost micro-circuits to generate the intrusive signature. The IS Strip can provide accurate event detection when there are only one or two appliances connected to the circuit.

Acknowledgments

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