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Context-Aware Plug-Load Identification Towards Enhanced Energy Efficiency in the Built Environment

Author
K.R., Krishnan

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Context-Aware Plug-Load Identification Towards Enhanced Energy Efficiency in the Built Environment

Krishnanand K.R., Hoang Duc Chinh, Manish Gupta, and S.K. Panda
Electrical and Computer Engineering Department
National University of Singapore, Singapore
E-mail: krish@nus.edu.sg, elehdc@nus.edu.sg, manish.gupta@bears-berkeley.sg, eleskp@nus.edu.sg

Costas J. Spanos
Electrical Engineering and Computer Sciences Department
University of California
Berkeley, CA 94720, USA
E-mail: spanos@eecs.berkeley.edu

***Abstract*— It is not uncommon to employ energy labeling schemes on appliances or plug-loads that provide information regarding their expected energy usages and efficiencies. But this often does not include a follow-up action of checking whether the expectations on energy consumption are achieved or not for a particular appliance item being used. Automation of this task requires a mechanism that is context-aware regarding meta-data of the appliances (electrical ratings, energy-label information, etc.), and also aware of their operational-data consisting of real-time electrical measurements. In this work, a novel socket hardware is proposed which can access the meta-data and operational-data of appliances in an automated fashion, such that a supervisory control system can contextually identify the plug-loads for intelligent demand side management. The proposed smart cyber-physical system would enhance energy efficiency in future buildings, and would also reduce electronic waste.**

Keywords*— buildings; internet of things; plug-load identification; smart socket; smart grids;

I. Introduction

The rapid urbanization around the globe, along with the pressure that it creates on energy requirements, necessitate proper planning of modern buildings and better management of their energy consumption [1-2]. With the evolution of low-cost hardware with embedded intelligence [3], the modern buildings see an influx of active components that can be communicated with and controlled. This is inclusive of wirelessly controlled nodes of actuation, which facilitate distributed control of devices in the building [4-5]. Topics on energy savings using fixed loads such as lighting in commercial buildings [6] and centralized air-conditioning [7] have already been investigated, and new methods of addressing the control have been prescribed by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [8-9].

Meanwhile, the task of plug-load reduction has been difficult because of the limited understanding of energy efficiency opportunities and equipment needed to address energy use in office spaces. Typically, no single decision maker can specify all efficiency strategies for plug-loads, which makes centralized educated decisions about possible strategies difficult. The owner, tenant, engineer, architect, information technologies procurement staff, and facility operator all can make decisions about plug-loads. Furthermore, most plug-loads are not included in ASHRAE 90.1 and are typically not addressed by building codes [10]. This implies difficulty in the design phase itself of a *building-grid* (the electrical infrastructure within a building), meaning the plug-loads cannot be entirely decided before the building starts to serve its occupants.

Managing appliance information for the informed decision-making of humans is not new. Electrical appliances are regulated to have product labels and rating labels which specify details such as country of origin, product description, warnings, user instructions, and compliance marks, such as Conformité Européene (CE) marking [11] or Waste Electrical and Electronic Equipment (WEEE) symbol [12].

There have also been efforts towards energy labeling schemes and improving the end-user's understanding of appliance efficiencies. Examples include Energy Star introduced by US Environmental Protection Agency [13], European Union's (EU) Energy Label [14], Energy Rating label in Australia and New Zealand [15], and an international database of efficient appliances [16]. The labeling schemes may differ in nature as to whether they are comparative labels or endorsement labels. Examples for EU's Energy Label are shown in Fig. 1.

While these information are available for visual inspection of humans and assistive mechanisms like “Digi-Label” are being popularized [17], there is no automated mechanism by which a real-time supervisory control system (SCS) of a building can know whether an appliance is connected to a socket or not, and it is inherently ignorant regarding technical specifications of the appliances. This inhibits the ability of the SCS to inform the occupant regarding energy consumption in real-time, to follow-up on the claims expressed in Energy Labels, and to reduce standby power consumption by parasitic

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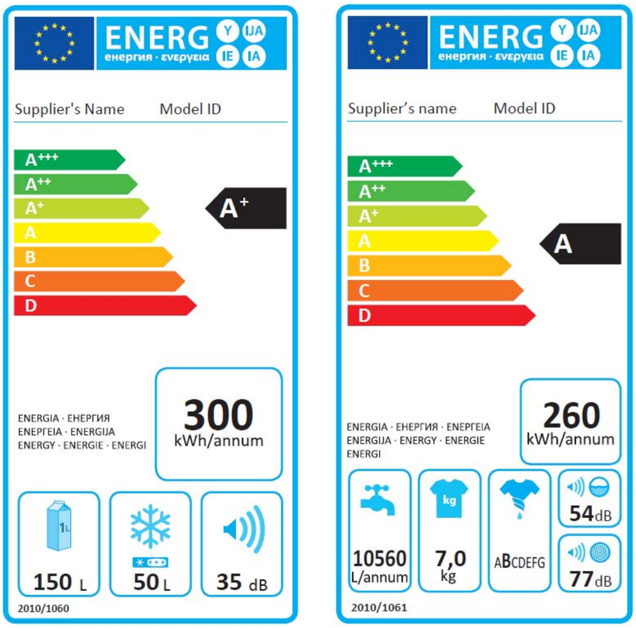

(a) (b)

Fig. 1. Samples for EU's Energy Labels a) Label shown for a refrigerator specifying its meta-data such as supplier's name, model identifier, energy efficieny class, annual energy consumption (AEC) in kWh per year, storage volumes, and Airborne acoustical noise emissions b) Label for a washing machine with its own meta-data.

loads [18] through confident automations.

Currently, the building-grid is neither intelligent enough to know which appliances are connected to it, nor what the characteristics of appliances are. This situation becomes much more complicated when the human interaction with the building-grid and the appliances are considered. The plug-loads can be displaced, relocated, change ownership, deteriorate in performance, or malfunction. In large commercial buildings, asset management operation on hundreds of appliances purchased, such as tracking location and performance, could be very difficult. There are no easy ways to determine under-utilization of devices either. It could lead to purchase of redundant and unnecessary appliances. These issues affect the objectives of sustainability energy-wise, and they result in electronic waste.

This work proposes a novel smart electrical outlet/socket that makes the building-grid smart enough to accurately identify and measure the plug-loads connected to it. This context-awareness subsequently allows automated methods to track the actual performance of the plug-loads and compare it with their energy labels. It also provides a real-time inventory which would mitigate redundant purchase and use of unnecessary plug-loads. Resultant energy savings thus achieved lead to improved energy efficiencies of buildings.

The next section discusses the existing technologies that are considered as smart plugs/sockets, and their drawbacks. Section III details the novel electrical socket and its architecture. Section IV contains the examples of operation of the novel socket ecosystem to uniquely identify plug-loads and measure their consumption, so as to contextualize the appliances' states. Section V is the conclusion and future work.

II. Existing Configuration and Technologies

An example of the electrical plug at the end of flexible cable of appliances usually used in Singapore is given in Fig. 2. The electrical terminals are marked as L (meaning 'Live', also known as 'Phase', with a color code of 'brown'), N (meaning 'Neutral', with a color code of 'blue'), and E (meaning 'Earth', also known as `Protective', with a color code of 'green and yellow'). The fuse is typically rated for 13 A and the plug is recognized as Type G by International Electrotechnical Commission (IEC) [19].

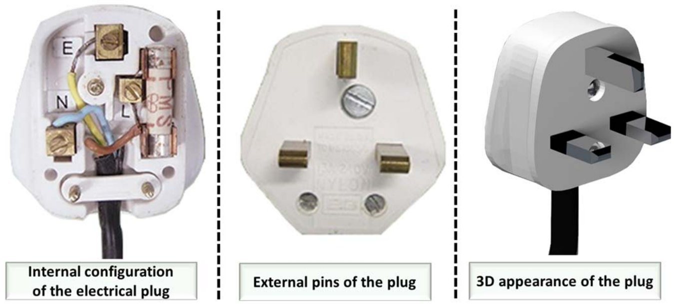

Fig. 2. A typical electrical plug of appliances used in Singapore [19-20].

The recent years have witnessed a commercial rise in smart-home automation, and smart plugs/sockets that are portable sockets which are used by plugging them into a conventional electrical socket of the building-grid [21-22]. 'Smart plug' is the common name for the smart device which is used in between the conventional socket and the conventional plug.

Smart plugs typically depend on wireless communication technologies such as Wi-Fi, ZigBee, or Bluetooth [23]. The smart plugs in an indoor area connect to a common gateway device which relays information to the Graphical User Interface (GUI) accessible by the human-users and facilitates control of the smart plugs, if that option is provided. The general scheme of operation of smart plugs is illustrated in Fig. 3.

The gateway device might contain the software to manage the smart plugs, or might act as a mediator to connect the plugs to a Supervisory Computing System (SCS). In Zigbee based devices, a master-unit is common [24]. The Wi-Fi based smart plugs could utilize the existing Wi-Fi routers within the building. Also, Wi-Fi brings appliances closer to the vision of IoT (Internet of Things) [25].

The abilities of smart plugs vary with the vendors, but the most common function is on/off control of the electrical supply to the appliances through mobile apps (applications) [26]. Whether such control is possible from anywhere, or only within certain proximity of the common gateway device, would depend on the network configuration. Smart plugs might also monitor energy usage at the electrical outlet, with options for storing the historical data. Other than energy, root mean square voltage and current also might be measured. Such abilities are useful in the idealistic conditions, and are not without drawbacks in the practical scenarios, especially for large buildings.

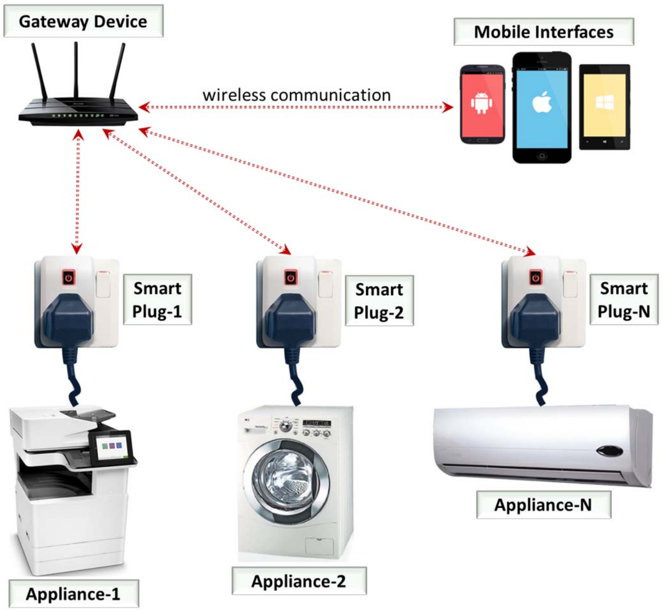

Fig. 3. General scheme of operation of smart plugs that communicate.

Since the smart plugs are portable, they are more or less limited to homes where the number of sockets is only a few. They are not physically secured in a particular location and always rely on the continued caution of the end-user. Generally, the human-user has to fix the smart plug at a conventional socket and the appliance connected to that smart plug, and then the user has to map them one-to-one using a software interface provided by the vendor. But the difficulty is that this mapping can change from the accidental switch of the appliances connected to the plugs, due to an action from the user at home, or the replacement of an appliance with a newer or different one [27]. The smart plugs could also be relocated.

These invalidate the confidence that an SCS can have in monitoring and controlling the loads within a building. Considering commercial/office buildings, where multiple humans interact with numerous appliances, such smart plugs are quite impractical. This consequently serves as one of the major hindrances in achieving smart-grid operations for buildings.

The following shows an estimation of the space for error:

- Let the number of conventional sockets within an indoor space be S.
- Let the number of smart plugs be P, and that of appliance be A. Most common scenarios follow $S \geq P$ and $S \geq A$.
- Let the total count of theoretical configurations for connecting appliances and smart plugs to the conventional sockets be T. The conventional sockets are embedded in the wall, making them different from one another with respect to their location within the indoor space. Any wall-socket could be with or without a smart plug, and with or without an appliance.
- That means, the total count of possible combinations are

$$T = S.\,(P+1).\,(A+1) \quad (1)$$

A residential apartment will have S in the range of 10-20, and a commercial building would have wall-sockets in hundreds. While only one configuration is set by the human-user through the GUI, thus informing the SCS, there are (T-1) erroneous configurations possible. A few impacts of the plausible errors are:

a. The monitored data streams from different appliances could get wrongly assigned to each other due to the swapping of appliances or smart plugs.
b. The energy from identical appliances belonging to different users cannot be differentiated when plugged into the same smart plug at different times.
c. The SCS might try to switch on/off an appliance that has been displaced from its manually mapped position.
d. The SCS might try to incorrectly switch on/off an appliance that has been newly introduced to the location of a previous appliance.
e. Incorrect data streams and incorrectly done control actions could cause the errors to accumulate and escalate when computationally processed by SCS. This would render energy calculations and carbon footprint estimates invalid.
f. Sending wrong information to the users would subsequently introduce error in judgment of the users too.
g. These difficulties can be overcome through the novel hardware and software ecosystem proposed in this work. To avoid such errors and to have realistic context-awareness in future buildings, a novel Smart Electrical Outlet/Socket (SEOS) technology which is capable of intelligent identification, monitoring and control of plug-loads has been developed.

III. Smart Electrical Outlets/Sockets (SEOS)

SEOS ecosystem entails electrical socket hardware units that are driven by corresponding software, the combination of which allows the socket to do the following:

- ✓ Uniquely identify each and every tagged electrical plug-load that gets plugged into the socket hardware
- ✓ Perform real-time voltage and current measurements
- ✓ Perform active power, reactive power, and energy measurements
- ✓ Identify certain power-quality events
- ✓ Communicate digital data wirelessly to another machine with corresponding software and
- ✓ Perform on/off control of the electrical supply.

The abilities of SEOS are achieved through physical integration and coordinated operation of the following components:

i. The electrical conductors that typically allow connection between the appliance and the building-grid. The conventional electrical sockets already have these.

ii. An apparatus for measurement of electrical parameters (voltage, current, their waveform characteristics, active power, reactive power, energy etc.) in real-time using an Integrated Circuit (IC) that is fed by voltage and current sensors. The voltages and current sensors sense instantaneous values of electrical parameters, which include power-quality information too.

iii. A controllable relay which allows turning 'on' and 'off' of electrical supply to the plug-load.

iv. A near-field reader which can read near-field communication tags or chips that comes within 5-10cm proximity of the reader. The near-field communication takes place at 13.56 MHz. This is used for Plug-Load Identification (PLI).

v. A long-range communication module which can transmit and receive data with another machine. Wi-Fi is preferable because it has become common in the indoor environment of urbanized areas. There are alternatives that are common in the broader IoT domain such as Zigbee and Bluetooth.

vi. A processor or computing hardware which handles the operation of the IC, the relay, the near-field reader and the communication module. This part is the local brain of the SEOS hardware.

The low-power functional parts which provide the smartness to SEOS hardware are shown in Fig. 4 schematic.

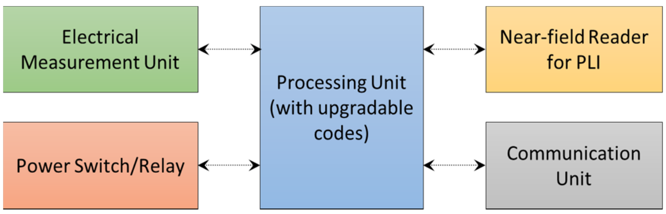

Fig. 4. Schematic of the novel smart socket developed is shown.

The near-field reader and the energy measurement unit acquire local non-electrical and electrical information, the power switch/relay provides control, and the communication unit allows data transfers. The processing module runs the programmatic subroutines required for the connected components to function. SEOS has been developed in two forms: a) wall-socket and b) portable-socket. The portable socket is similar in physical dimensions to other socket extenders and smart plugs, thus confirming its practical usability in buildings. An internal structure of a portable-socket is shown in Fig. 5 and its outer view in Fig 6.

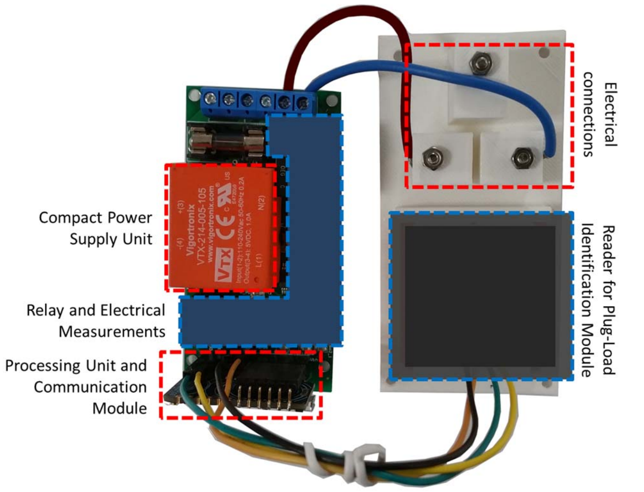

Fig. 5. SEOS portable-socket's labelled internal structure.

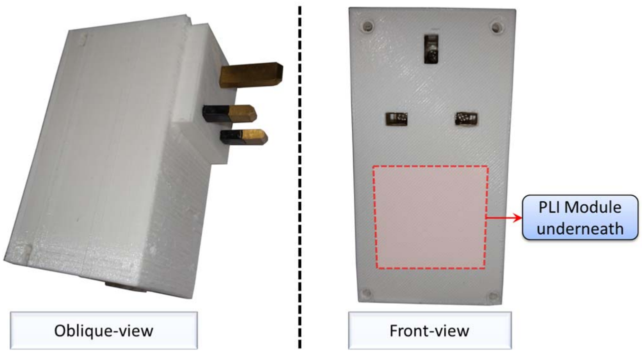

Fig. 6. SEOS portable-socket's 3D-printed casing's oblique-view showing the pluggable pins, and also its front-view.

IV. SEOS Ecosystem's Operation and Results

SEOS hardware had to be initially tested for the primary functions of appliance identification and monitoring of electrical parameters. For that purpose, a stand fan and an LCD desktop monitor were connected to a hardware unit of SEOS, which then identified the appliances based on the near-field tag information that were placed on them.

The electric fan was rated for 49-55.5 W for a voltage range of 220-240 V at 50 Hz. The other details associated with it were that it belongs to climate class 'T', its blade diameter is 40 cm, its "safety mark" number issued by the regulatory authority, the manufacturer's name, model information etc. The desktop monitor was not connected to a display input, yet had a standby state where it waits for the switch-on button on the front to be pressed and another state after pressing that button. The monitor was rated for a maximum of 1.5 A RMS current. Such information was made available to SEOS through the PLI module, upon which SEOS could contextualize the electrical information measured. The sequence of appliance interaction with SEOS with associated measurement is shown in Fig. 7 and 8. It is clear that SEOS has the option to turn off appliances and avoid their standby power consumption with due consideration to what the actual appliance is. A real-time web-interface to

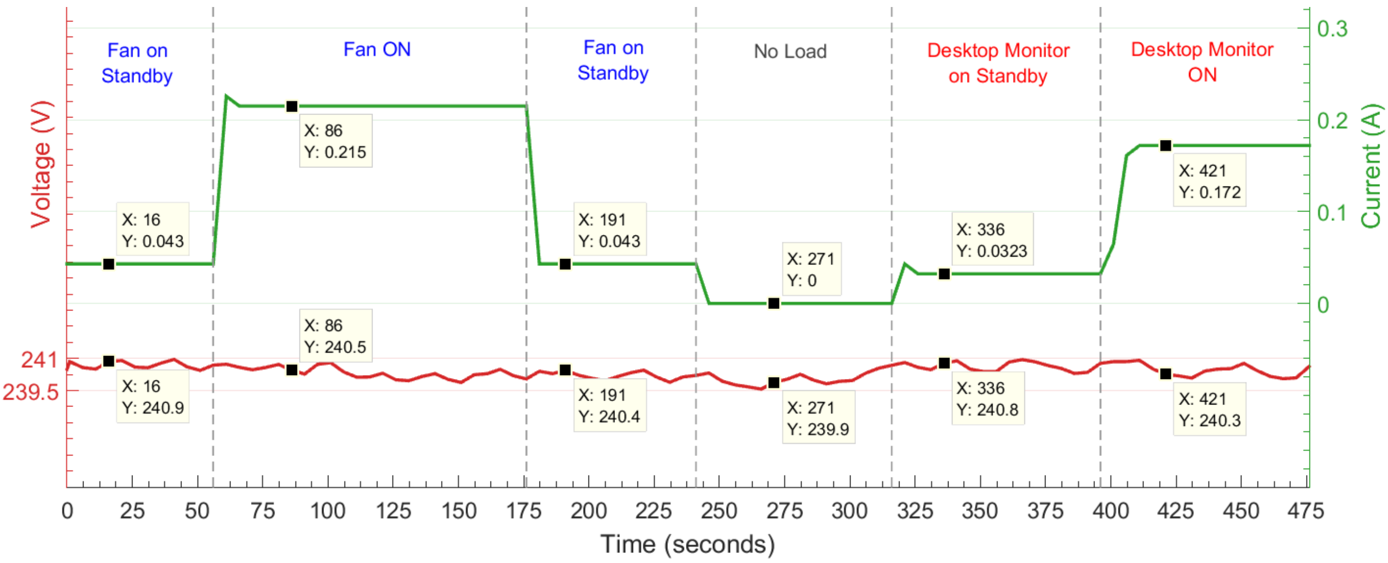

Fig. 7. Voltage and current measurements by the proposed socket, for different kind of load conditions

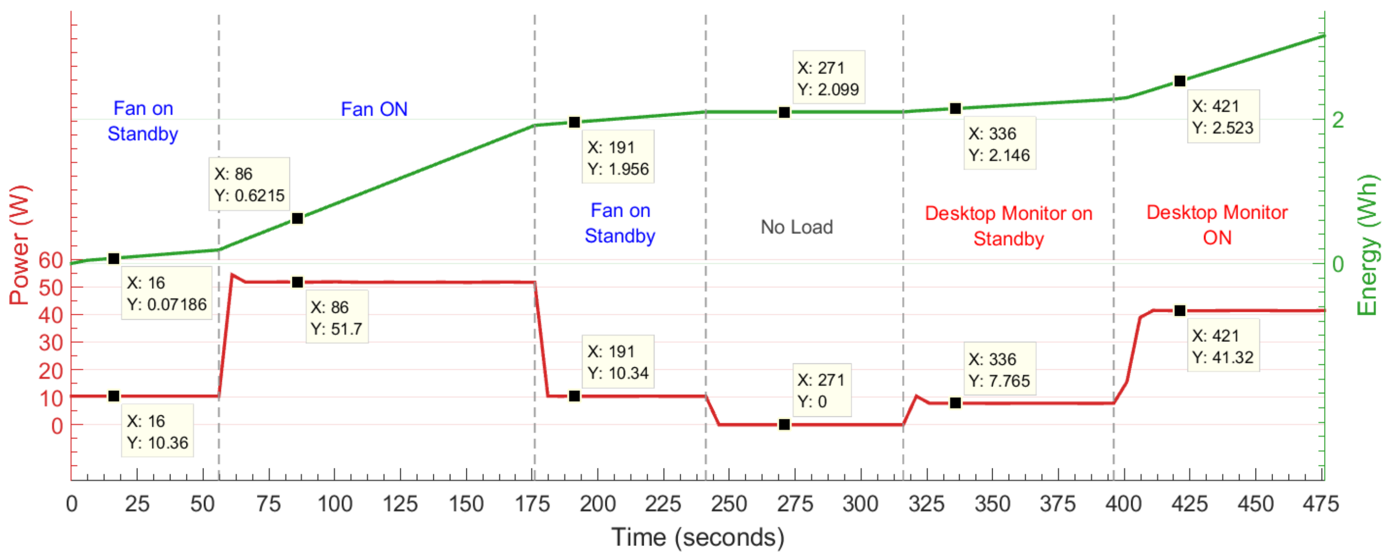

Fig. 8. Corresponding power and energy values computed by SEOS

track appliance usage is shown in Fig. 9. These illustrate the basic yet unprecedented abilities of the proposed SEOS ecosystem.

V. Conclusion and Future Work

This research has presented a novel Smart Electrical Outlet/Socket (SEOS) ecosystem which contains a new socket hardware and corresponding supervisory computing system to uniquely identify potentially any plug-load. SEOS contains a plug-load identification mechanism, thus providing it unprecedented functionalities and making it a gateway technology for many novel applications. A significant application is to access Energy Label and/or the electrical rating information automatically when appliance is connected to the socket, and compare them with actual measured performance, thus forming realistic understanding of energy consumption patterns. Since the meta-data of the plug-loads are available to a supervisory computing system, including the product details, SEOS can also avoid redundant appliance purchases in large institutions and hence reduces electronic waste.

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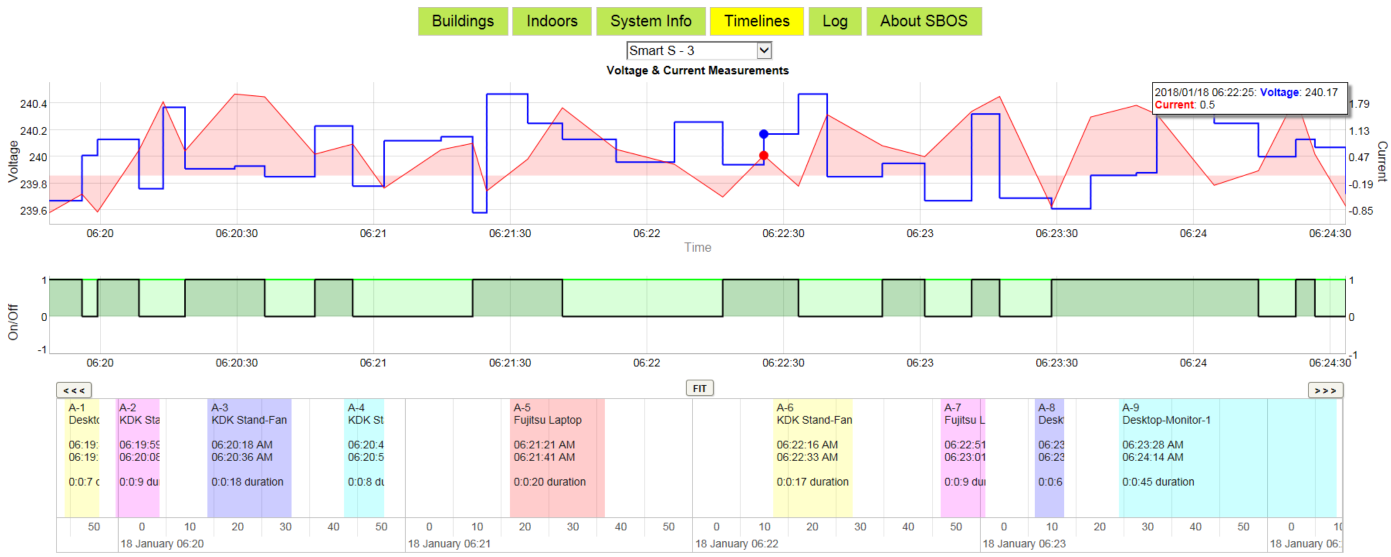

Fig. 9. Real-time web-interface showing plug-load identification and contextualization using SEOS. Since the appliance information is automatically available for the SCS through the SEOS ecosystem, any energy saving scheme of appliance scheduling can be done more intelligently, and in a robust manner.

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