A WIRELESS SMART GRID TESTBED IN LAB[1]

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The authors present *SmartGridLab*, a wireless communication based laboratory environment testbed for Smart Grid research

ABSTRACT

State-of-the-art Smart Grid design needs innovation in a number of dimensions: distributed and dynamic network with two-way information and energy transmission, seamless integration of renewable energy sources, management of intermittent power supplies, real-time demand response, and energy pricing strategy. To realize these, we have designed *SmartGridLab*, a wireless Smart Grid testbed to help the Smart Grid research community analyze and evaluate their designs and developed protocols in a lab environment.

INTRODUCTION

A Smart Grid is a form of electricity network utilizing digital technology. Smart Grid delivers electricity from suppliers to consumers using two-way digital communications to control appliances at consumer level. This saves energy, reduces costs and increases reliability and transparency.

In existing (centralized) power grid, the basic principle of transferring energy from power plant to a large number of users cannot often meet the increase in demand. To resolve this problem, the trend is to seamlessly integrate the sources of renewable energy, and allow distributed power generation. This necessitates a scalable grid structure connecting distributed sources of energy supply and consumers, and offers better disruption resilience.

However, there are a number of open research problems in designing practical Smart Grid. The main difference between a traditional grid and a smart grid is that the latter relies more on communication between consumers, suppliers, smart devices and applications. The power networks and information networks shall be integrated into Smart Grid network for bidirectional data flow, control flow and energy flows.

Other open research problems include: *price driven real-time demand response*; *disruption resilience with self healing*; *management of intermittent power supplies*; *dynamic pricing*; *reduction in energy loss*; and *scheduling of power consumption to constrain peak load*.

To enable the development, analysis, and evaluation of different algorithm and protocol solutions to these problems in a smart grid, is the motivation behind building the *SmartGridLab* testbed. It uses 802.15.4 wireless network (configured as a wireless mesh) to emulate the smart grid network. We have also performed a number of experiments related to some of the above open problems for showing the usefulness of *SmartGridLab*.

SmartGridLab TESTBED DESIGN

The proposed *SmartGridLab* testbed consists of four main components: (a) an information network containing Power Meters, (b) Intelligent Power Switch (IPS), (c) energy supplier (main supply, and renewable energy source as solar panel and wind turbine), and (d) energy demander (e.g. appliances). They are described below.

Architecture of Information Network: In a smart grid, two-way communication will allow information exchange. *SmartGridLab* uses 802.15.4 wireless mesh network in the testbed prototype. This information network is a kind of wireless sensor network and the power grid is the object it would sense. SmartGridLab testbed can be easily extended with other communication interfaces such as WiFi radio or Ethernet, since our architecture is flexible and does not depend on a specific communication mechanism.

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[1] The preliminary version of this work was published in the IEEE SmartGridComm 2010 conference [12].
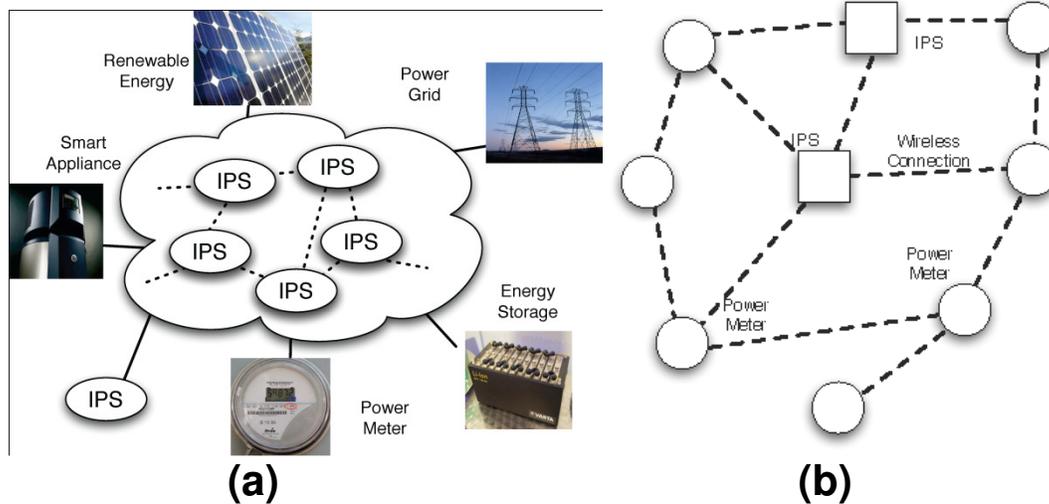
Figure 1. (a) Power network architecture. **(b)** Wireless Information Network in *SmartGridLab*.

Figure 1(b) shows the currently used wireless information network in *SmartGridLab*, although the system is made flexible enough to integrate other modes of communication.

The network can be configured to work in centralized or distributed mode. In the centralized configuration, the power meters can send their data to an Energy Management Center (*EMC*), which can compute the status of the whole power grid and send out control information signal. On the other hand, in the distributed configuration, each microcontroller on IPS will compute its own status based on the information it has received from other IPS and power meters. Each IPS and power meter can communicate with each other and exchange their status.

Architecture of Power Network: Figure 1(a) illustrates the overview of the power grid, using IPS, which is a device that can re-route power flow from one input to another. It has a microcontroller with wireless communication components. IPS can be connected to energy sources (including renewable energy and power grid), smart appliance, energy storage, power meter and also to other IPS. Therefore, IPS is a critically important component for achieving smart grid architecture. Based on this feature, the grid that contains IPS can be configured into different topologies. For example, IPS can be connected as mesh, tree or ring, and also the configuration can be changed as desired.

Figure 1(a) shows a distributed architecture of power grid in which the distributed power suppliers and consumers are connected to the cloud of IPS. By connecting to IPS, a new component can easily be added into the power network. In this power network, no centralized control is needed. Rather it is like a peer-to-peer network. IPS can be connected to current power grid system and it can also act like a micro-grid. It can group the devices connected to it and can isolate from the main power grid if any disturbance is detected.

In other words, IPS can also be outside the large IPS cloud and be the gateway of a home area network of appliances.

IPS DESIGN: As mentioned, IPS is the critically important component for achieving distributed and scalable architecture, and it needs to efficiently control the interconnection of components. The purpose of IPS is to switch power from one port to another. The hardware of IPS is shown in Figure 2(a). At the same time, multiple pairs of ports can be connected together.

To achieve these, IPS uses the design as shown in Figure 2(b), which depicts a six-port IPS. Fifteen switches are used to control six ports. If more ports are used, there should be more switches. For example, suppose the requirement is: Port 1 only supplies energy to Port 3, and Port 2 only supplies energy to port 4. To achieve this, close S11 to connect Port 1 and Port 3, and then close S7 to connect Port 2 and Port 4.

In the IPS hardware design, TelosW [8] sensor mote platform is used as controller of IPS. It can send out control command to shift register. Our design uses two shift registers, each having 8 outputs, and each output can control one of the switches. IPS can get power directly from the power line. In this design version, the power supply should be independent from all the six outlets. In the next version of IPS, we plan to use a rechargeable battery to supply power to TelosW and the switches. It can then be charged whenever one of the six outlets is connected to the power supply. Solid state relays S116S01 are used as power switch. S116S01 can provide 4.0 kV isolation between input and output, while the peak off-state voltage is 400V. By using this device, it is easier to control high voltage AC by low voltage control signal.
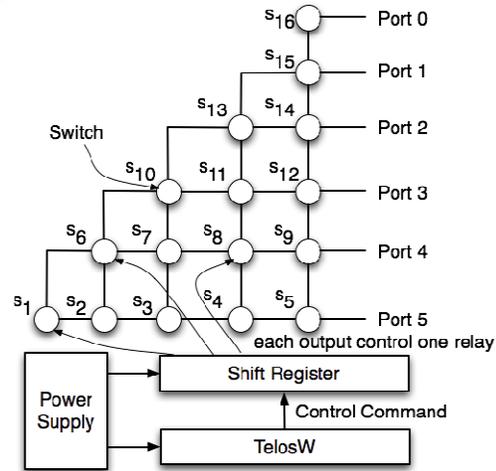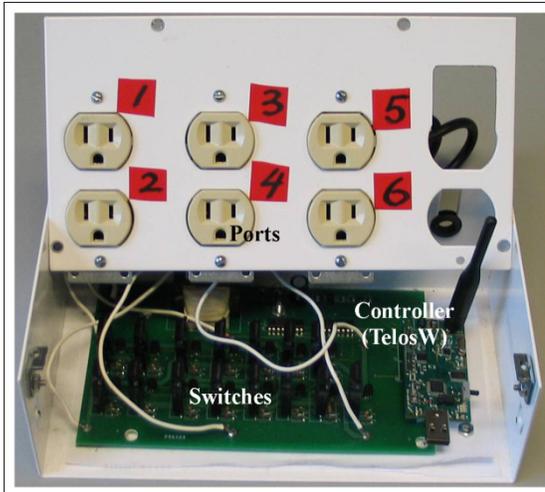
(a)   **(b)**

Figure 2. (a) Intelligent Power Switch (IPS) hardware with input ports. (b) Intelligent Power Switch Design.

POWER METER DESIGN: Power meter is another important component in the proposed *SmartGridLab* testbed. It can measure how much current is flowing in the test line. The power meter shown in Figure 3(c) is designed with four parts: TelosW sensor mote, Hall effect current sensor, resistor network and power supply. TelosW is the controller of power meter. Hall effect current sensor converts current value to voltage. The design uses ACS714 5A version with 1.2 mΩ internal conductor resistance. So its energy consumption is negligible. The output of ACS714 is linear according to the current change on the test line. The output of ACS714 can be converted to digital numbers by an analog to digital convertor (ADC), so the current value can be processed by microcontroller.

However, the output voltage of ACS714 varies from 1.5 V to 3.5 V, while the ADC on TelosW can only allow a maximum of 2.5 V input. Thus a resistor network is needed to regulate the input below 2.5V. It can get power supply directly from power line, and the output is stable 5V to ACS714 and TelosW.

The hardware of our power meter is shown in Figure 3(a). We use MSP430F1611 as microcontroller and its own ADC to sample data from Hall effect sensor. Considering the frequency of MSP430F1611 [9] (which is only 8MHz) and the data rate of wireless radio, if the sampling rate is set as 0.1mS, the power meter cannot send out all data to the *EMC*. So local data processing is necessary. The flow of this process is shown in Figure 3(b).

First, 512 samples are taken from the ADC in each 0.1mS. After this is done, root mean square (RMS) is computed based on these samples. In AC signal, RMS can indicate the average current. Once this is done, the final result is sent to the EMC through radio communication.

One problem in this flow is that the RMS computation may take a significant amount of time. However, the energy consumption of appliance will not change very quickly, so the computation of RMS can be performed at a low rate. In our testbed, we take 1 second interval between two computations of RMS.

ENERGY SUPPLY AND ENERGY DEMANDER: In our testbed, either wall outlet power, or renewable energy sources can be used as power supply. They can be connected to IPS to provide energy to the rest of power network. Figure 4(a) shows two micro renewable energy generators. They are small enough to be used in laboratory experiments to evaluate smart grid protocols and algorithms.

As energy demander (i.e., consumer) we have used lamps, computers and other appliances. We have also designed a smart appliance (Figure 4(b)) that can intelligently control the energy usage according to price signal of supplied power.
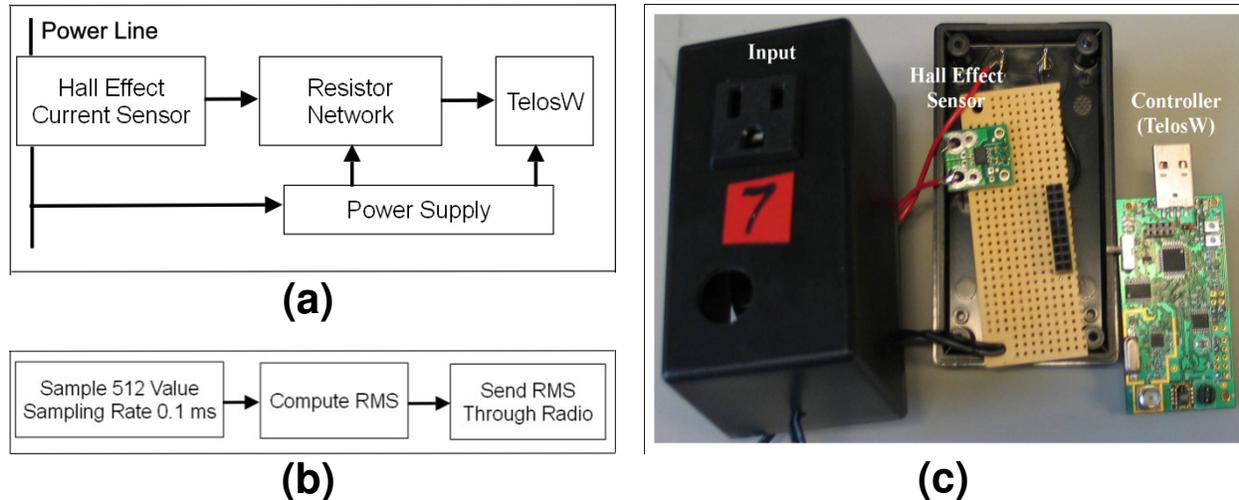
Figure 3. **(a)** Power Meter Design. **(b)** Computation in Power Meter. **(c)** Power Meter Hardware with power plug.

TESTBED VALIDATION

Various research problems can be studied using the *SmartGridLab* testbed. In this section, we will demonstrate its usage with smart grid experiments. Six IPS are used here and the connection between them is shown as in Figure 4(c).

In our experiments, we have configured these IPS into a mesh power network. However other kinds of topology could also be formed by IPS. On the connection of each IPS, there is a power meter to measure power flow between them. Two power supplies, P1 and P2, provide power to the network. They are connected to switches S1 and S4.

We use three lamps to emulate appliances. They are indicated as A1, A2 and A3 in the figures shown later. A1 and A2 are connected with S5, while A3 is connected with S6. In the figures, the real power meter readings are shown. The experiment setup snapshot in shown in Figure 4(d).

REAL-TIME DEMAND RESPONSE: The fluctuations and uncertainties of different energy supplies pose challenges in controlling them coordinately for provision of energy demand, as well as scheduling consumers' demand. This necessitates Demand Response (DR) techniques (e.g. [11]). We have conducted experiments related to two demand response strategies: (a) reliable energy supply with multiple intermittent sources, and (b) price driven demand response with multiple flow.

(a) Management of Intermittent Power Supplies: In this experiment, we simulate two renewable energy sources with intermittence on each of them but the intermittence does not happen at the same time, and the appliance still gets a continuous power supply. In Figure 5(a), the first two plots are two power supplies with intermittence.

We simulate them by turning on and turning off the connection of switch to the power supply. From these two plots, it can be observed that none of them has continuous output. The third plot in the figure is the energy consumption of appliance (A1, 100watt is used), and the energy supply has been stable.

(b) Price Driven Demand Response with Multiple Flow: Our experiment is to show that multiple power flow can co-exist by using IPS. In Figure 4(c), A3 is a 40 watt lamp which gets energy from Supply P1 through path P1→S1→M1→S2→M6→S6→A3, while A1 is a 100 watt lamp which gets energy from Supply P2 via path P2→S4→M7→S6→M8→S5→A1. The two paths can co-exist in this network according to the reading of power meter. Even though they have an intersection in S6, they will not interfere with each other.

DISRUPTION RESILIENCE WITH SELF-HEALING: Disruption resilience is one of the key features of a smart grid. The link from supply to consumer may be broken at some point. The smart grid should have the ability to switch path from the broken link to another one. In this experiment (Figure 5(b)), appliance A2 and supply P1 are used. First, A2 is connected with P1 through path P1→S1→M1→S2→M6→S6→M8→S5→A2. The link between S2 and M6 is broken. Then the path from P1 to A2 is switched from the original path to a new path P1→S1→M2→S3→M5→S5→A2.

FLOW BALANCE USING MULTIPLE PATHS: In this experiment, A1 (100 watt) and A2 (60 watt) are connected into the network, and they get energy from P1. However, all flow is coming from path P1→S1→M2→S3→M5→S5, and the other part of the network has no flow. Assuming that each line's limit becomes 100 watt, so this path is overloaded.

(a)

(b)

(c)

(d)
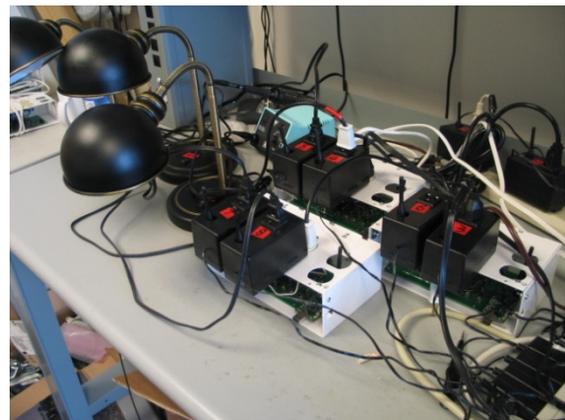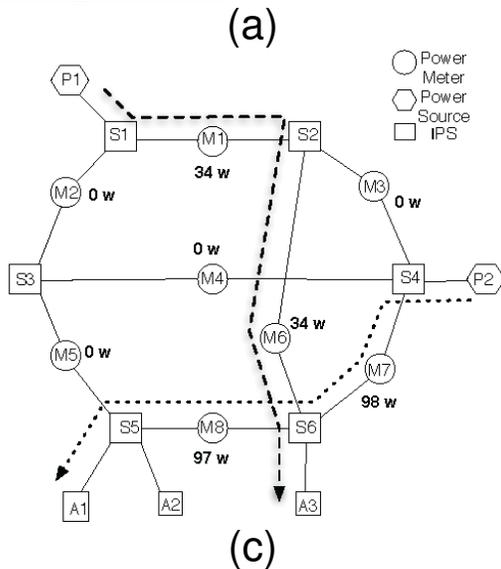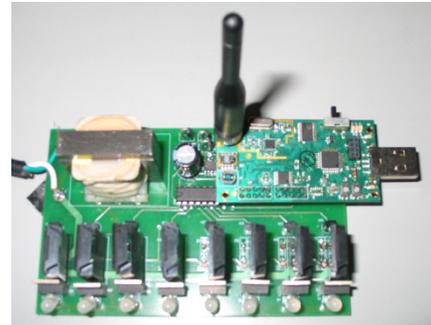
Figure 4. (a) Renewable Energy Sources. **(b)** Smart Appliance Design. **(c)** Multiple Flow: A1 (100 watt) gets energy flow from P2, while simultaneously A3 (40 watt) gets energy flow from P1. The real energy flow measured across lines are also shown. **(d)** Experimental setup.

To satisfy the limit, we still connect A1 to P1 with the same path as before, but switch A2 to another path P1→S1→M1→S2→M6→S6→M8→S5→A2. Figure 5(c) shows the flow (1) before balance and (2) after balance.

POWER METER: To validate power meter, we have set up two experiments. The first experiment uses three lamps (130V, 40W; 120V, 60W; 120V, 100W) as load. We turn them on one by one and get readings from power meter. From Figure 6(a) demonstrates that our power meter can precisely reflect the changing power consumption, and the power meter reading is fairly stable and accurate over time.

In the second experiment, a laptop has been connected with the power meter. The energy consumption is measured for more than an hour as shown in Figure 6(b). We first charged the battery from 85% to 100%. In the middle of this process, we run graphical editor software, so there is a spike at 1000 second. After charging battery, we made the computer go to sleep mode, therefore energy consumption drops to about 15 Watt. In the last part of this figure, we turn on video processor software which uses about 80 Watt.

These all experiments show the applicability of our designed *SmartGridLab* testbed for the Smart Grid research community.
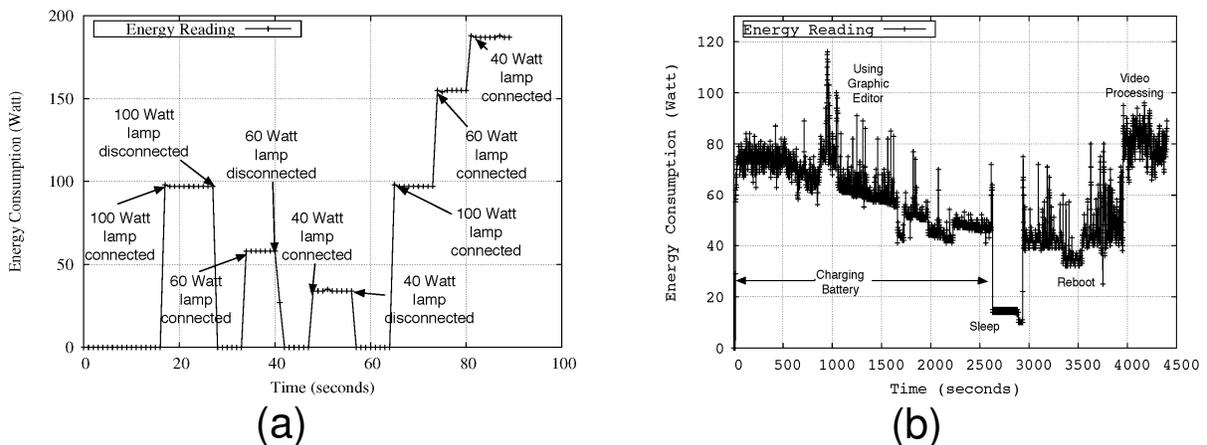
CONCLUSION

This paper presents *SmartGridLab*, a laboratory environment testbed for smart grid research. In this testbed, the main components are: Intelligent Power Switch (IPS), different sources of power supply, energy demander, and power meter. IPS enables the power grid to be configured as any kind of topology, and the power meter senses the energy flow on each line and reports the data.

The information network is co-designed with power network. *SmartGridLab* can significantly help researchers to analyze, evaluate and compare various algorithms and protocols developed for smart grids. Several experiments are performed to show the applicability and usefulness of our testbed for the Smart Grid research community.
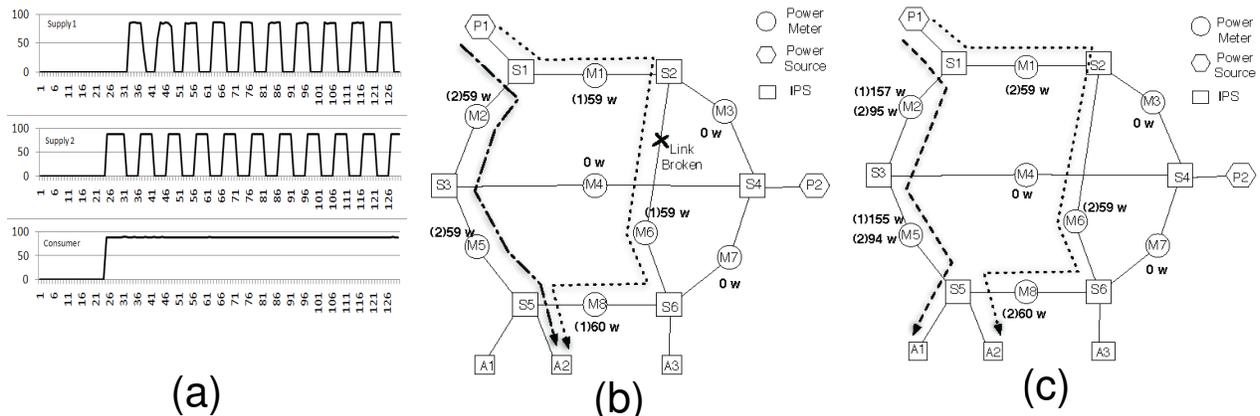
Figure 5. (a) Management of Intermittent Power Supplies: A1 getting continuous power from two intermittent sources of power supply. **(b)** Self Healing: A2 (60 watt) initially gets energy flow from P1. When the link from S2 to M6 is broken, self healing smart grid assigns a new path from P1 to A2. The real energy flow measured across lines is also shown. **(c)** Flow Balance with Multiple Paths: A1 (100 watt) already getting energy flow from P1. Then for A2 to get energy flow from P1, the smart grid assigns another path for maintaining balance in energy flow through lines. The real measured energy flow across lines is also shown. Power Meter readings shown: (1) before flow balance, (2) after flow balance.

Figure 6. (a) Validation of Power Meter. **(b)** Energy Consumption (measured with power meter) of an Apple MacBook during different operations.

In conclusion, the work of *SmartGridLab* is unique in a sense that it is one of the early efforts to build lab-scale Smart Grid testbed yet supporting all key features for large variety of experimentations.

As future work the *SmartGridLab* is being added with more features like energy control module for renewable energy sources, energy storage module etc.

Acknowledgement

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