

Smart Power Outlets with Cross-layer Communication

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Abstract— Smart grid is expected to extend its ability to optimize power usage control intelligently. We made an end system called Smart Power Outlet (SPO), which effectively functions as a control unit in home and factories. SPO estimates power usage of connected electric appliances, determines to approve their power use or not, and selects in-house branch circuit from which approved appliances draw currents. Connecting SPOs, we need standard which has high universality and strong flexibility because they are to be used in multi-vendor environments and to traverse over administration and technical layers. In this paper, we formulated requirements for such cross-layer communication, and propose a practical frame work satisfying the requirements, and show application examples. Also, we show two typical models of power usage control, i.e. request-approval model and broadcast-margin model. Thus, we propose and verify a practical communication frame work to be used as a basis for evolving smart grid.

Keywords— Smart Grid, Smart Power Outlet, Cross-layer Communication, Universal Communication Format, Centralized Control, Distributed Control

I. INTRODUCTION

For safety, energy saving and convenience, every electrical equipment and appliance will be monitored and controlled by some remote software in a near future. To make it possible, we have to provide a universal standard to be used by all equipments and appliances in communication with software. Current movement for developing smart grid is a good trigger for such formation of standard. Though, it will be a very hard work to make a universal, long lasting and practical standard for a wide range of equipments and appliances.

To form smart grid fundamentals, standard development by assorting existing standards is a practical approach[1,2]. However, it tends not to provide a simple and universal tool to connect relevant software, equipments and appliances. If the standard does not applicable or not suited to all of them, there will appear many narrow targeted and/or proprietary schemes, which would retard the realization of integrated communication environment. The most important targets for the standard are consumer equipments and appliances, because they are enormous in number and rich in diversity.

In this paper, we start with analyzing essential requirements for the universal standard, show a basic frame work for it and practical application using the frame work. In the application, we concentrate on smart power outlet which will be described

in detail later. The most steady steps to consolidate a standard are applying and modifying. We think that the smart power outlet is a typical and practical application as a end-user appliance at our current consumer's electrical environment.

II. REQUIREMENTS FOR THE STANDARD

We start with analysing basic requirements for a standard, because we do not know a document which describes how to design a standard, although there are some documents which describes how to describe a standard[3,4]. Requirements for the standard may be summarized in four characteristics.

A. Commonness

The first and the most important one is commonness to all of the targets. We have to make clear the commonality among the targets and form a standard based on it. Partial commonalities should be defined as selectable items. Also, data should be expressed in a common format.

B. Flexibility

The second may be flexibility, which enables the standard to be used for a long time with adapting it by adding new features and functions without modifying the standard itself. To form such a standard, it is effective to make its basics simple enough and to include a rule for adding new features and functions.

C. Compatibility

The third one may be compatibility with existing standards and actual practices. In a single phrase, "do not change once determined" could be the best strategy.

D. Practicality

The last one may be efficiency and applicability in real situation. In many cases, some exceptions from the standard may be requested and it would create confusions. Effective means to avoid such confusions are to use flexibility stated above, for example, to make local optimization.

The objective of the mutual communication in a smart grid is to exchange data such as current usage, current margin, current reservation and current reduction request. We should propose a standard which includes further capability such as the functions considered in Building Energy Management System (BEMS) and Home Energy Management System (HEMS).

E. Cross-layer Communication

Layered architecture is ideal to separate functional responsibilities and to keep implementation freedom inside the separated region. Interfaces between the layers should be defined by the smallest set of necessary communications. Users may be relieved if they can consider the electric power delivery system as the lower layer and supposed to be independent from their usage.

However, any system cannot be completely independent from others. Usually, every layer has some limitations inside or enforced from its lower layers. Upper layers must have relating limitations due to them. Without intelligent mechanism inside or between layers, top end layer, that might be human users, should care about all the limitations below them in the cases where the top end layer wants to utilize the full capabilities of its lower layers. We are now obliged to do it for energy conservation and reducing environmental human effects. Then, we need some mechanism to optimize the whole layers, while the system was structured in separate layers. A natural way to resolve the problem is to use a cross-layer communication (XLC).

F. Technical XLC and Management XLC

There are two types of layers for power delivery structures. One is technical layers, and the other is management layers. Fig. 1 shows three technical layers relating to our SPO. The physical layer includes wirings and connectors with some predetermined specification, such as voltage, number of wirings and phases. The power control layer includes current limitation, demand feedback and demand response. The application layer consists of electric power appliances. The layered structure is ideal for appliance designers and users, who do not want to care about the details behind. However, lower layer restrictions, such as contracted and safety current limitation, demand higher layer applications and users to care about them.

If we implement a mechanism to control appliances according to the restriction in the power control layer, we need some responding software inside each appliances, which

virtually works as a power control layer (dashed boxes in Fig.1). It is an XLC between the control layer and the application layer.

Fig. 2 shows management layers in a horizontal direction compared to the vertical layers in Fig.1. From the left, power generating stations, transmission grid, distributors and consumers. Each layer is controlled by the corresponding management entity. It is ideal that any layer will not be influenced from the status of the other layers. However, we know that we should have mutual interaction to optimize the efficiency of the whole system. Power generating stations must agree with distributors, and distributors react demand of their consumers. To enable such XLC automatically, we have to generalize how to communicate across the layers and how to interact each other.

In a whole view, vertical layers in Fig.1 are stacked upon the horizontal layers in Fig.5, making the structure three dimensional. The requirements for XLC should enable cross-layer communications in two directions.

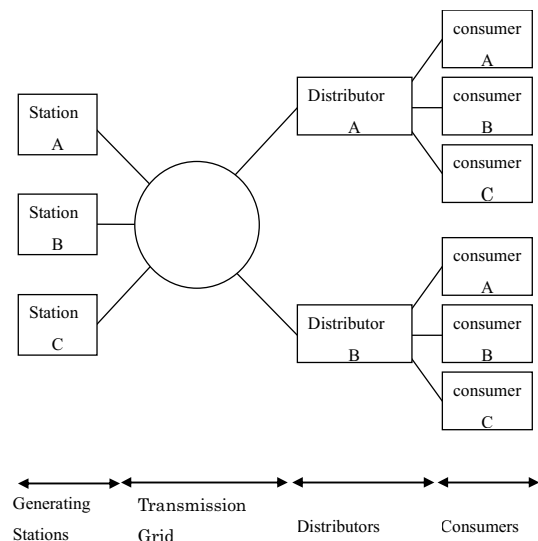


Figure 2. Management layers for power control.

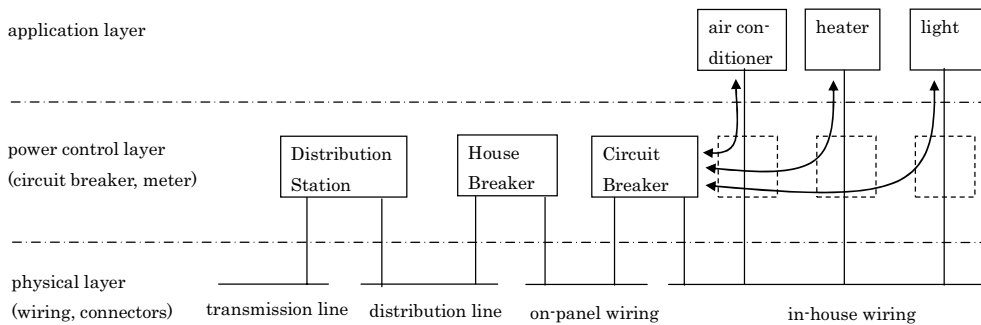


Figure 1. Technical layers for power control.

III. PROPOSED BASICS FOR THE STANDARD

Mutual communication can be defined by a protocol, which should be simple enough to be easily implemented in every appliances. In an extreme side of simplification, no need of processing on the intermediate layer is the best strategy, which can be attained by sending only the data that has instantaneous meaning to be processed by the end receiver.

Commonly accepted data format is XML, which represents data by using characters and suitable for commonly used character based data processing.

A. Universal Communication Format

As a common rule to express data with satisfying the requirement in the former section, we are proposing a data format called Universal Communication Format (UCF) which expresses communication data in a practical but abstract format [5,6]. It uses XML style and consists of destination tag <A> and data content MSG as in

```
<A>MSG</A>
```

which expresses MSG sent to object A. To include the information that the sender is B, the expression will be

```
<A><s>B</s>MSG</A>
```

The object s is an inner object in A, and it processes the return address B for replying.

B. Commonness

Any communication carries a message sent and received. If there are more than one receiver, any sender must specify the receiver for its message. Then, receiver specifications and messages are common things for all the networked communication. UCF corresponds to minimum requirements for any communication because it simply expresses a receiver by the destination tag and a message by the content. Any communication can be decomposed to such pair expressions.

C. flexibility

Extensibility of XML style expression is valuable for adding new messages without affecting existing software. To enable XLC, there must be some addressing scheme for accessing an object in other layer or beyond some layers, by which both software in different layer can communicate and cooperate.

A common and universal addressing scheme across layers can be attained by relay-based source routing addressing scheme [5]. An example expressed in UCF is

```
<A><B>MSG</B></A>
```

which means a compound message MSG to be sent to A. And A will relay it to B. It is infinitely expandable by chaining relaying objects (name tags) before and after the original message.

D. Compatibility

Even if we select XML as our format of data representation, there is vast freedom of data representation, what to represent and how to represent. Nobody can determine perfect what and how. So, we have to make choice with great caution and have

to do continuous modification for connecting the past and future choices.

Two rules are important. The first one is to use lower layer terms in XLC. In our smart grid case, electric current is common to all the layers. For example, if the control layer software needs to indicate an appliance to reduce its power usage to a certain amount, the software can tell the appliance with electric current value and the appliance would understand. But it cannot tell with temperature settings to an air conditioner because the control layer does not know the relation between temperature and current usage.

The second rule is only to add new data terms which have no effect on existing software and appliances. In the extremity of this rule, default settings or implicit assumptions must be preserved for ever. If we have to change it, we should make a new communication object. We formalize this rule by defining software objects which have certain implicit assumptions with giving a unique name to each object. If we need a new object, we must give it a new name.

E. Practicality

An XML style character based data expression increases the volume of data. However, character expression is the only universal method of data expression and many network software can accustomed to handle it. Then, practically, the only universal data expression is character based one. To reduce the volume, character based data compression and content based data reduction can be used with outputs in XML style data expression.

IV. SMART POWER OUTLET

Electric power delivery system is a basic infrastructure for modern societies. We want to use it as an ideal utility, which will not be influenced by our usage. However, every physical utility has some limitation, such as maximum current. And we have to adjust our usage within the limitation in order not to trigger a circuit breaker. If we want to implement an automatic mechanism for dealing with such limitation, we need some intelligent software having communication ability between units concerned[1,7-8].

Circuit breaker is also a typical example of non-intelligent component which responses only with an anachronistic behaviour of power cut off in response to consumer's excess demands. We would like to expect a friendly response, at least, such as sending a "overload" warning message to the user. If the power delivery system can accept and schedule appliance's demand, it enables not only to eliminate unnecessary power outage, but also to function as a power manager, which can limit the total usage, responding to a request from its contracted power distributor.

However, it needs some mechanism to hold the demanded appliance in a wait state, which should be implemented in every appliances. We made an intelligent outlet control unit called Smart Power Outlet (SPO) for retrofitting such a function to existing appliances.

Fig.3 shows a circuit diagram of our SPO, which can intelligently connect three appliances to two breaker circuits

(AC 100V, max 20A). Normally, appliances are connected to the circuit A through a resistor (500 ohm). If we turn on any of them, the current transformer (CT) coupled to its feeding line detects the current and sends the current value through a current meter to the programmable logic controller (PLC).

The PLC calculates the current that the appliance will consume when connected without the resistor, assuming it as a pure resistance appliance. Next, it looks for a circuit which affords the calculated current, and connect the appliance to the circuit found by switching two relays. If there is no circuit which affords the current, PLC keeps the appliance waiting. When an appliance stops operation and a current meter detects it, the PLC identifies the connector port and switches off the relay connected to it. Then, it connects the waiting appliance to an available circuit.

Fig. 4 is a photo of a prototype SPO. We used Hitachi Industrial Equipment System EH-WA23DR as the PLC, and Panasonic Electric Works KW7M as the current meter. The resolution of the current meter is 0.1A and its sampling interval is one second. We confirmed the functions of the unit. It could detect turning on and connect up to two appliances for two circuits by using electric Kettles and a hair drier which consumes more than 5A. We are upgrading SPO to use analogue inputs of the PLC, so that it can calculate appliance's current with higher resolution and connects in less than a second.

When we have several outlet places, we want to install more than one SPO as in Fig. 5. In that situation, SPOs have to communicate each other for sharing the current capacity and keeping the total current under the limit for all the circuit breakers. Also, they need to get limitation and allowance information from the house current meter. Then, we have to make a specification about the mutual communication among units concerned.

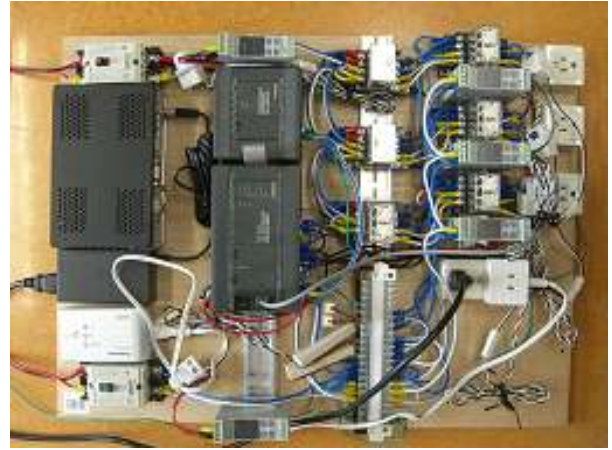


Figure 4. A prototype of Smart Power Outlet.

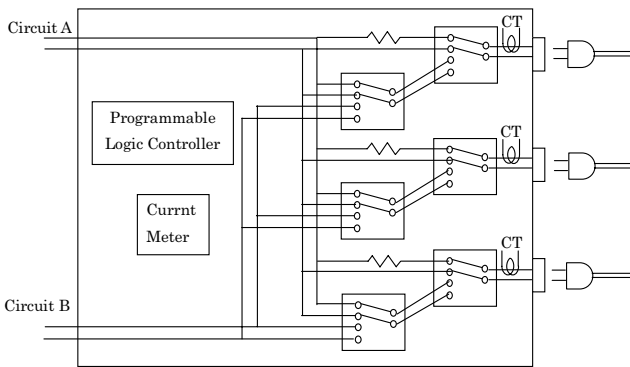


Figure 3. Smart Power Outlet circuit diagram.

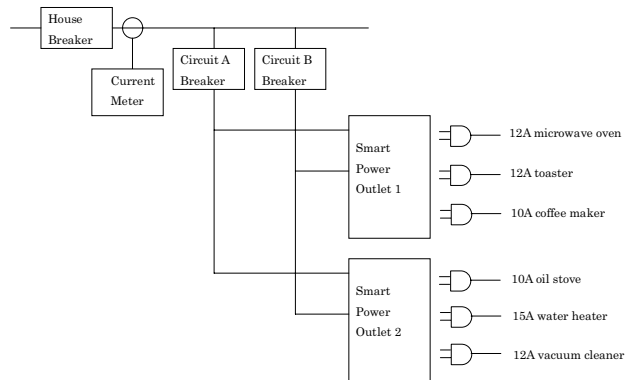


Figure 5. Example of a house with multiple Smart Power Outlets.

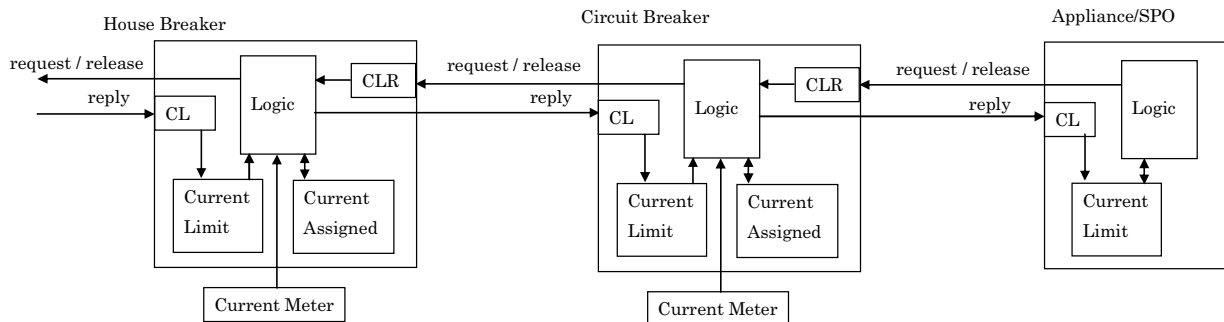


Figure 6. SPO communication objects for request-approval scheme.

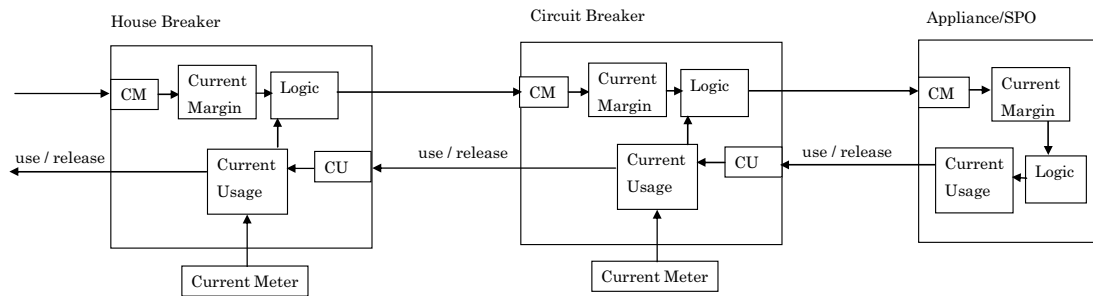


Figure 7. SPO communication objects for broadcast-margin scheme.

V. COMMUNICATION EXAMPLES FOR SPOS

We show two types of mutual communication and control model in this section.

A. Objects for Request-approval Scheme

In request-approval scheme, any appliance which wants to use current needs to request permission from its upstream controller and can use only after getting the permission.

Fig.6 shows three controllers in a hierarchy and detailed objects for request-approval control. The right one corresponds to SPO, whose function would be installed in ever appliances in future. CLR is a software component in the circuit breaker (CB) for updating current usage (CU) register. CL is for setting current limiting (CL) register. If an appliance “HeaterABC123” is turned on, it request its upstream circuit breaker for estimated amount of current by sending

```
<CB><CLR><s>HeaterABC123</s> 10A</CLR></CB>.
```

The message requesting to allow 10A usage is destined to CLR object in object CB. Tandem tagging <CB><CLR> means that the message is to be sent to CB, which relays

```
<CLR><s>CB<s>HeaterABC123 </s></s>10A</CLR>
```

to CLR. If CLR accepts the request, it sends back

```
<HeaterABC123><s>CB<s>CLR</s></s><CL>10A</CL></HeaterABC123>.
```

When the heater completes its operation and returns its right to use the current, it sends

```
<CB><CLR><s>HeaterABC123</s>0.1A</CLR></CB>.
```

where 0.1A is its standby current. CB can do the same communication with its upstream current controller, i.e. house breaker (HB). In an ideal centralized mode, current request and release should be forwarded to the head end controller.

If upstream controllers are forming hierarchy, request-approval process needs time to go up and come down. However, it is efficient in power usage because they can give permission up to the total limit which the head end controller keeps. In a practical system, request granularity for current should be increase at an upper level controller, so that the lower level controller return permission quickly by using locally kept store of current allowance.

B. Objects for Broadcast-margin Scheme

In broadcast-margin scheme, controller broadcasts current allowance amount to all the downstream devices in advance. Each appliance keeps the margin inside, and it can immediately use current up to the margin. It must report the amount it uses to the upstream controller, immediately.

Fig.7 shows objects for a broadcast-margin control. The following UCF message is to be sent from appliance “HeaterABC123” to the circuit breaker.

```
<CB><CU><s>HeaterABC123</s>10A</CU></CB>.
```

The upstream controller subtract it from its margin and broadcast the renewed margin value. If the controller needs to suppress the usage, it sends

```
<HeaterABC123><CM><s>CB</s>-5A</CM><HeaterABC123>.
```

which indicates “HeaterABC123” to reduce its current usage 5A less.

In this scheme, any appliance can determine whether it can use current or not, quickly. However, there is a possibility that more than one appliances start to use current. If the temporal total usage surpass the limitation, the controller which detected such situation must send a reduce message to appropriate down stream units as shown above. Naturally, each breaker must limit the total current through it to the amount of its predetermined limit.

We are now examining the above schemes by adding a small PC in the SPO, which handles UCF messages. SPOs are connected through HD-PLC(High Definition Power Line Communication, max 190Mbps) shown in Fig. 4 as a white box in the left side. The PC and the controller PLC are connected with twist pair Ethernet (100Mbps). The PLC and current meters are connected with RS485 (19.2kbps). The processing time and the communication delay between PCs and PLCs are relatively small compared to the sampling interval (1s) and the averaging delay (2-3s) of the current meters. Then the response time of SPO is around one second for appliance’s power on processing and around two-to-three seconds for power off processing.

VI. DISCUSSION

XLC is needed for optimal control over the layered system. But it must not spoil the stability of the whole system. Independent objective of each layer management may conflict against the other layers [9]. Safe usage of XLC should be sought.

Central control for request-approval scheme is simple to design, but has a difficulty of handling large number of target appliances and a risk of whole system collapse by some defect or delay of the central controller. Distributed control for broadcast-margin scheme may show complex behavior, but has self healing mechanism if the interaction between the components are properly designed. Current management layers assumes independent distributed control in each management region. Therefore, we should start with distributed control scheme. And, if we need further optimization, we are to use XLC as a tight control between specific objects.

Security measure should be taken in the communications described. In UCF, it is easy to encapsulate any message with encryption such as, `<A><enc>xxxxxxx</enc>` where xxxxxxxx is encrypted string and decrypted by the object enc. By this way, XLC can be encrypted with keeping the relay mechanism, still functioning by using the unencrypted part of the message.

VII. CONCLUSION

Smart Power Outlet (SPO) is introduced as a tool to intelligently control existing electric appliances. Communication between SPOs or between SPO and other devices are needed for further intelligent control with capability of cross-layer communication. We showed requirements for such communication, and proposed a data format UCF for enabling and representing XLCs. And also, we showed practical example of SPO communication for centralized and distributed control.

Development of smart grid needs control scheme. XLC is a preferable scheme of optimization for layered control structure. We are implementing our XLC control over SPOs. And also, we plan to investigate dynamic characteristics by using a simulator which is dedicated to UCF message handling (Fig.8). Using UCF as the communication data format in real applications and, also, in simulation, we can easily connect simulation and real objects for developing software and testing system function and performances[10].

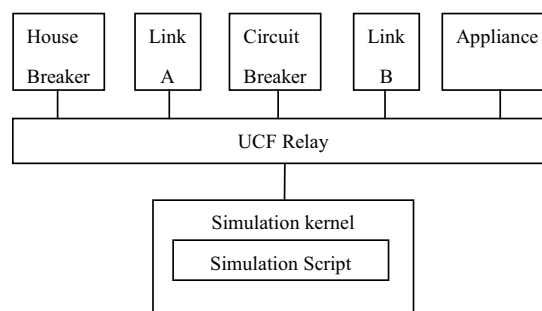


Figure 8. UCF simulator configuration.

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