PlugStar: a low cost Solution to control Domestic Loads with dedicated SmartPlug

Giovanni Galioto*, Natale Galioto*, Costantino Giaconia*, Laura Giarré*, Giovanni Neglia+, Ilenia Tinnirello*
*Department of Electrical Engineering, Universitá di Palermo, Italy
email: *name.surname*@unipa.it
+Maestro project, INRIA, Sophia Antipolis, France
email: *name.surname*@inria.frt

***Abstract*—Balancing energy demand and production is becoming a more and more challenging task for energy utilities. This is due to a number of different reasons: the steady increase of energy consumption and fossil fuels' price, the larger penetration of renewable energies which are more difficult to predict and control, and finally the meagre availability of financial resources to upgrade the existing power grid. In this paper we consider a scenario where DLC functionalities are deployed at a large set of small deferrable energy loads, like appliances at residential users. The required additional intelligence and communication capabilities may be introduced through *smart plugs*, without the need to replace older "dumb" appliances. Smart plugs are inserted between the appliances plugs and the power sockets and are already produced with a variety of different purposes: prevent vampire power drain, monitor energy usage and generally reduce the overall costs to run various electronics.**

I. Introduction

Direct Load Control (DLC) allows energy utilities to control electric loads at the customers' premises. In the past DLC was used in critical situations to prevent blackouts by shutting down these loads. More recently, an extensive use of DLC has been advocated as a way to shape energy demand peaks. Direct load control is a mechanism that allows electric utilities to turn specific users' appliances on and off during peak demand periods and critical events. The problem has been largely studied in literature with several proposals formulating the control mechanism under different optimization objectives, related to the power grid reliability or operation savings. The usual approach is based on a *central controller*, working on the basis of dynamic programming optimization (1), fuzzy logic-based decisions (2), or other profit maximization schemes (3). Recently, some utilities have been involved in pilot projects enrolling real users in direct load control programs. The appliances considered in these programs are usually limited to air conditioners, water heaters and pool pumps (4; 5). In (4) the control signal is based on the traditional monitoring of the power-grid voltage and frequency signals, in order to detect critical load conditions in terms of variations of the expected signals. Users appliances were modified to respond to the under-frequency signals by reducing their energy demand. Conversely, in (5), an energy management device, connected to the utility controller, has been provided to the users for switching on and off traditional (unmodified) appliances. In both the cases, investments have been required for modifying the appliances or deploying the control network.

We consider a scenario where DLC functionalities are deployed at a large set of small deferrable energy loads, like appliances at residential users. As we are going to discuss, the required additional intelligence and communication capabilities may be introduced through *smart plugs*, without the need to replace older "dumb" appliances. Smart plugs are inserted between the appliances plugs and the power sockets and are already produced with a variety of different purposes: prevent vampire power drain, monitor energy usage and generally reduce the overall costs to run various electronics.

Load control in modern power grids is becoming more and more important for maintaining a balance between energy supply and demand. Traditionally, the demand was much more variable and less controllable than supply, so that the energy balance was achieved by adapting dynamically generation levels to match the consumption. The increasing penetration of renewable energies has radically changed the scenario, due to their lower predictability. The possibility to control power demand is then becoming more appealing for several actors, such as the energy utilities (that can better plan the production as well as control the grid reliability) and the end customers (that can actively participate to the energy market). Two main approaches are envisioned: demand-response and Direct Load Control (DLC). The first expression refers to end users changing their normal consumption pattern in response to a dynamic price signal. DLC denotes the possibility for the electric utility (or some third-party entity) to directly control remote electric loads.

However, despite the many proposals in the literature for demand response approaches (6) or direct load control (1; 3), the control of residential users' energy demand (which significantly affect the overall energy load variability (7)) is still limited to pilot projects (4; 5) with little penetration perspective in the near future. The reason is that the implementation of these mechanisms requires investments (for updating user appliances and communication infrastructures) which are not clearly justified for the end users.

In recent papers (8),(9) the authors investigated a realistic deployment and low-cost path for large scale direct control of inelastic home appliances whose energy demand cannot be shaped, but simply deferred. The idea is to exploit 1) the Internet connections of customers for transporting the admission control requests and 2) some simple actuators to be placed on the electric plugs for connecting or disconnecting non-smart appliances. Our solution requires no interaction with home users: in particular it does not require them to express their energy demand ahead of time. The proposed solution, called PlugStar, enables direct load control for deferrable appliances in a large scale power grid, with very limited infrastructure investments for communication and appliances control. While the proposal of PlugStar architecture can be found in details in (10), the performance evaluation have been first presented in (8) and its extension to the case when appliances' power consumption is a random variable and the bound on the aggregated power is probabilistic was presented in (9).

Indeed our approach does not require any change to the appliances, but relies on some devices that can be inserted between the appliances plug and the power socket. These devices are usually called *smart plugs* and are already produced with a variety of different purposes: prevent vampire power drain, monitor energy usage and generally reduce the overall costs to run various electronics. In PlugStar, their basic functionality is to be able to interrupt/reactivate the current flow once they receive a command from a remote controller that may be managed by the energy utility itself or from some another entity like an energy aggregator (11; 12; 13). In this way the smart plug can simply postpone the appliances operation reducing the instantaneous power demand. The command is relayed to the smart plug from a home gateway connected to the Internet. The communication between the smart plug and the gateway requires then some local communication protocol, like Ethernet, WiFi, ZigBee, BlueTooth, etc.. The gateway may be simply an application running on a PC, on the ADSL box or even on a smartphone. In many countries a large percentage of the households is already provided with a Local Area Network (often a WiFi one) connected to the Internet. In this case the cost to deploy the solution at a home is basically limited to the cost of the smart plugs. At the moment of writing, there are already commercial devices which can accomplish all the functionalities required and whose price is less than 40$ (14). This cost would significantly decrease if such devices would find a large scale deployment as it is required for the application we envisage. Our solution could also take advantage of the diffusion of smart power meters with more sophisticated communication capabilities than the actual ones. In the present paper we describe a different SmartPlug solution that we design to be inserted in the Smart Plug architecture.

The contribution of this paper is to describe the smart plug architecture and its interaction with the power grid.

SmartPlug is a solution for implementing direct load control of deferrable domestic appliances with minimal user discomfort. The application has been designed in order to require very limited infrastructure investments for communication and appliances: when the user tries to activate a deferrable load, a simple actuator placed on the electric plug is able to send an activation request to a local energy gateway, which in turns

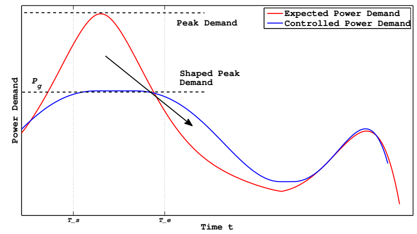

Fig. 1. PlugStar shaping action on the expected power demand.

is connected trough the Internet to the server performing the admission control; on the basis of the admission outcome, the gateway sends the commands to the actuator for disconnecting or connecting the electric (non-smart) appliance. Different goals can be pursued according to the employed admission control logic and to the actors (energy utilities, transmission system operators, or community of users) involved in the control.

Use Cases. Different use cases in which the SmartPlug application can be adopted for supporting an admission control logic at different aggregation levels can be considered.

- Medium Voltage/Low Voltage (MV/LV) line: This level of admission control can help to foster the integration of distributed generation from renewable sources in electrical MV networks. An adequate control of the load, indeed, based on the variations of the power injected by not dispatchable generators, can attenuate some of the typical problems of voltage regulation in the MV lines. Furthermore, the possibility to operate actions of peak-shaving and/or load shifting in the hours of maximum load may allow, in many cases, to delay interventions to strengthen the lines with high thermal stress.
- High Voltage/Medium Voltage (HV/MV) station: Similarly to the previous case, the control actions enforced by the energy utilities on the demand side can help ease the regulation process of the voltage profile in the network, since the set-point in the automatic regulator of the station affects the voltage profile across the entire MV network. For advanced systems, with a management mode inspired to the smart-grid model, this second level of control may also participate in the control of the frequency, especially in emergency conditions in which the grid may operate in stand-alone configuration.
- Power System Zone: While the control actions at the previous aggregation levels are implemented by the electric utilities, the third level admission control can be performed by community of customers for responding to price signals, with the goal to make elastic the power demand in the electricity market. For this type of applications, the control of the energy consumption can be realized on quite long time scale (from several hours to several days).

Architecture.

PlugStar is based on a usual client-server architecture: a central admission control server interacts with a set of clients belonging to the same MV/LV line, HV/MV station or price zone (i.e. with set of customers grouped according to their physical location on the power grid). The application works by shaping the power demand profile as conceptually shown in Figure 1, where the red curve represents the expected power demand and the blue curve is the actual demand under admission control. Note that PlugStar does not change the total energy demand (the area below the curve) on a long time interval, but it can shape the instantaneous power demand by postponing the operation time of some appliances, for example with the goal to satisfy a power cap P_g. The power demand exceeding P_g is then shifted to a subsequent time interval. The power cap may be originated by power transmission constraints, by production constraints or by too high production costs the utility would incur to generate energy during the peak time.

Figure 2 shows the network nodes involved in the PlugStar deployment: at the local domain, the client processes run on a home gateway and control a number of smart plugs by means of a local area network technology; at the network domain, the admission control server exchanges messages with different groups of clients by means of Internet. The architecture is based on the reasonable assumption that an Internet connection is already active in almost all households, thus avoiding to deploy a dedicated data network. The home gateway can be a normal PC, ADSL box or smart phone with a 3G data connection. The smart plugs are remotely controllable plugs equipped with a local network technology, a power sensor devised to detect (and/or to measure) the energy required by the connected appliance, and a microprocessor able to run simple applications.

In the network domain, the client-side application running on the home gateways is responsible of joining the application server controlling its grid segment at the desired aggregation level. The server-side application implements an admission control logic which depends on the aggregation level of end customers. By tracking the current state of the controlled power grid, the server sends the control commands to the clients in order to provide deterministic or probabilistic guarantees that the total energy demand of a group of customers does not overcome a given (time-varying) threshold. To this purpose, the server continuously interact with the clients for collecting activation requests of new appliances, as well as notifications of successful activation and deactivation of the admitted appliances. Since all these messages are delivered through the Internet, no delay guarantees can be assured between an activation request and response. This makes the architecture suitable for admission control logics pursuing an energy peak shaving or price control, while it is less reliable for reacting to emergency grid conditions.

In the local domain, a control application running on the home gateway interacts with the smart plugs for collecting the activation requests, the activation/deactivation notifications, and other (more complex) data, such as the energy consumption of the plugs, when available. According to the programmed admission control logic, the activation requests

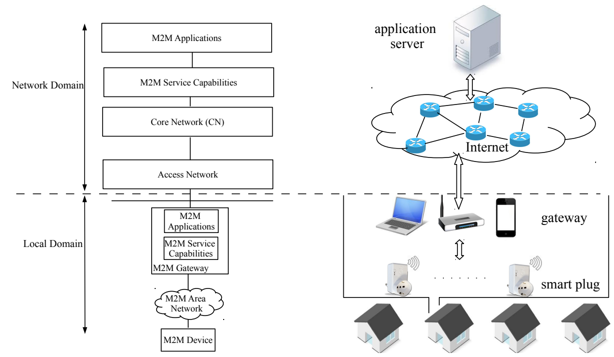

Fig. 2. PlugStar deployment in the local and network domain and mapping to the M2M high level architecture.

are immediately forwarded to the application server (8) or processed locally according to the signals periodically sent by the server (9). The messages exchanged between the home gateway and the smart plugs are typically sent through a wireless local area network working on unlicensed ISM bands (e.g. ZigBee and WiFi), where transmission reliability can vary significantly according to the experienced interference conditions.

Shaping the aggregated power profile can bring significant savings to the energy utility. Hence, customers installing PlugStar may be motivated to accept the deferral of their appliances by some economic incentives. If the PlugStar solution is managed by the energy utility itself, then these incentives may be in the form of some reduction of the users' electricity bill. Although we are not analyzing the most effective revenue sharing mechanism (e.g. uniform sharing, random extraction of selected users, etc.), we assume that customers perceive a reward proportional to the deferral time of their load requests (i.e. proportional to their discomfort) and to the energy consumed by the deferred loads after their admission. Such a solution disincetivizes customers from removing the smart plugs or implementing other misbehaviors.

In questo capitolo vengono descritte le componenti hardware e software che sono state utilizzate nell'ambito della progettazione di uno Smart Plug a basso costo. In particolare, dopo aver analizzato le caratteristiche di alcuni Smart Plug attualmente presenti nel mercato, si propone il progetto di una presa intelligente già dotata di interfaccia *Machine to Machine* e capace di eseguire delle applicazioni in locale destinate ad operazioni di elaborazione dei dati ed alla gestione immediata di alcuni eventi.

La progettazione del sistema ha riguardato sia la parte hardware che la parte software. A livello hardware è stato concepito un sistema *embedded*. Per esso sono stati tenuti in considerazione fattori importanti, quali dimensione effettiva e costo, che devono risultare competitivi con quelli dei prodotti già presenti in commercio. A livello software è stata adottata una soluzione che prevede l'uso di un sistema operativo Linux, una novità che consente l'utilizzo di apposite librerie Machine to Machine al fine di facilitare lo sviluppo delle applicazioni

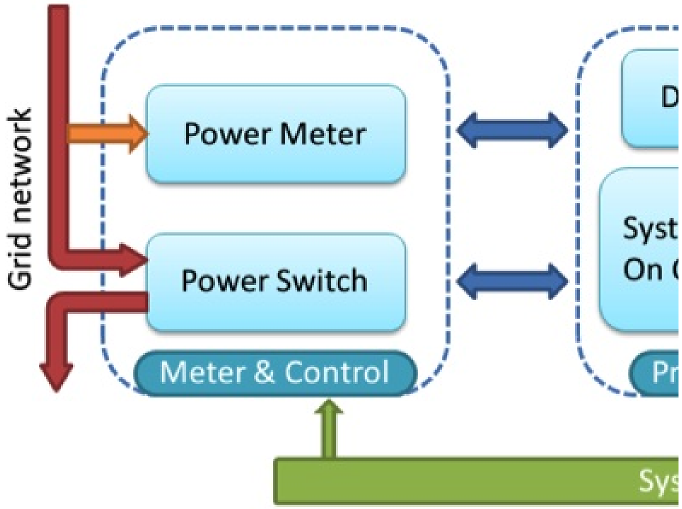

Fig. 3. Diagramma architetturale dello Smart Plug.

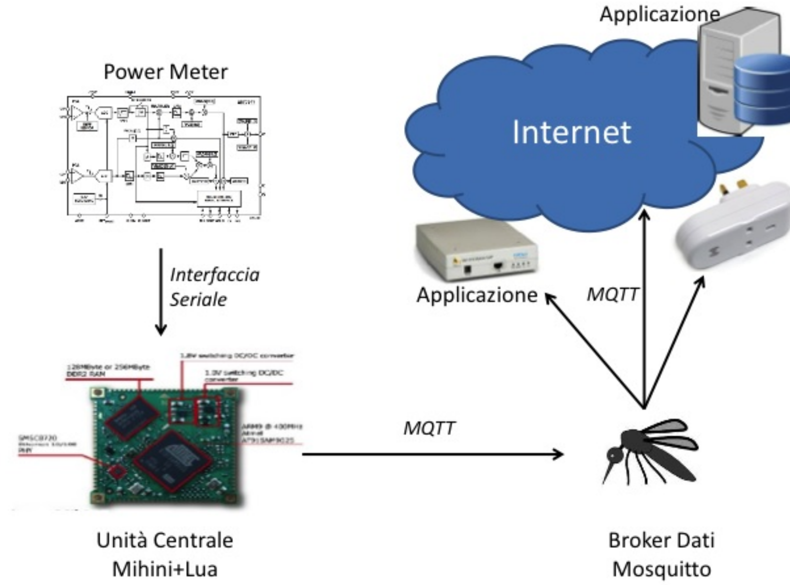

Fig. 4. Componenti hardware e software utilizzate per le applicazioni Smart Plug.

di controllo.

L'architettura hardware dello Smart Plug si basa su quattro sotto-sistemi fondamentali:

- **Modulo di elaborazione.**
  Rappresenta il cervello del dispositivo ed è incentrato sul componente SMD di tipo System On Module ARIA G25 della Acme Systems. Racchiude tutti gli elementi necessari per l'elaborazione quali processore, ram, e memoria dati per le operazioni di salvataggio permanente e di boot. Il suo ruolo è quello di eseguire le applicazioni di controllo e monitoraggio. A tal fine, fa uso dei dati provenienti dal modulo di misura e dal modulo di rete, mentre mette in atto le decisioni attraverso il modulo a relè.
- **Modulo di rete WiFi.**
  Garantisce la connessione all'infrastruttura della rete dati necessaria per l'interazione con gli altri dispositivi al fine di realizzare le applicazioni di controllo.
- **Modulo di misura dei consumi.**
  Permette la lettura del consumo energetico da parte del dispositivo, dato importante per le logiche di funzionamento locali e remote del sistema.
- **Modulo a relè.** Accende/spegne l'elettrodomestico collegato. Questo elemento altro non è che un interruttore controllato dalla logica del dispositivo, grazie al quale è possibile abilitare o disabilitare l'erogazione dell'energia elettrica al carico.

I quattro moduli sono mostrati in figura 3. A questi quattro elementi fondamentali si aggiunge il modulo di alimentazione, anche esso rappresentato in figura 3. Quest'ultimo non ha particolari accorgimenti. Infatti, poiché lo Smart Plug è perennemente connesso alla rete elettrica, è stato sufficiente derivare da essa la potenza necessaria ad alimentare le singole parti del dispositivo.

L'architettura software è invece basata su un framework denominato Mihini. Esso dispone di un contenitore di applicazioni all'interno del quale è possibile installare ed eseguire applicazioni M2M scritte con il linguaggio di programmazione Lua. Attraverso le librerie messe a disposizione dal linguaggio, le applicazioni accedono ai dati provenienti dal modulo di misura dei consumi, pilotano il modulo a relè ed utilizzano un protocollo denominato MQTT per lo scambio di informazioni su Internet (ad esempio la pubblicazione dei dati di consumo rilevati).

La figura 4 riassume i principali componenti hardware e software utilizzati per il progetto. Da essa si può notare anche la presenza del server Mosquitto, un componente open-source che supporta il modello *publish/subscribe* tramite *broker* (server intermediario).

II. Final Remarks

The role of direct load control in modern power grids has been shown to be beneficial for several applications. However, in the case of small individual energy loads, these benefits can be appreciable only if a large number of users are involved in the control process. Our solution requires no interaction with home users: in particular it does not require them to express their energy demand ahead of time. We present an architecture where smart plugs are remotely controllable plugs equipped with a local network technology, a power sensor devised to detect (and/or to measure) the energy required by the connected appliance, and a microprocessor able to run simple applications.

References

[1] Y. Y. Hsu, C. C. Su, Dispatch of direct load control using dynamic programming, IEEE Transactions on Power Systems 6 (3) (1991) 1056 1061.

[2] K. Bhattacharyya, M. L. Crow, A fuzzy logic based approach to direct load control, IEEE Transactions on Power Systems 11 (2) (1996) 708–714.

[3] G. B. Sheble, K. H. Ng, Direct load control-a profit-based load management using linear programming, IEEE Transactions on Power Systems 13 (2) (1998) 668–694.

[4] D. J. Hammerstrom, Pacific northwest gridwise testbed demonstration projects part ii. grid friendly appliance project, Tech. Rep. PNNL 17079, Pacific Northwest (2007).

[5] Fpl on call saving program, Tech. rep.
URL www.fpl.com/residential/energy_saving/programs/oncall.shtml

[6] V. Balijepalli, V. Pradhan, S. Khaparde, R. M. Shereef, Review of demand response under smart grid paradigm, in: Innovative Smart Grid Technologies - India (ISGT India), 2011 IEEE PES, 2011, pp. 236–243. doi:10.1109/ISET-India.2011.6145388.

[7] Buildings energy data book., Tech. rep.
URL http://buildingsdatabook.eren.doe.gov/default.asp

[8] G. Di Bella, L. Giarré, M. Ippolito, A. Jean-Marie, G. Neglia, I. Tinnirello, Modeling Energy Demand Aggregator for Residential Users, in: IEEE CDC, 2013, pp. 6280–6285.

[9] G. Neglia, G. Di Bella, L. Giarré, I. Tinnirello, Unidirectional Probabilistic Direct Control for Deferrable Loads, in: IEEE INFOCOM Workshop on Communications and Control for Smart Energy Systems (CCSES), 2014.

[10] Plugstar: a low cost m2m solution to control domestic loads.

[11] O. Abdalla, M. Bahgat, A. Serag, M. El-Sharkawi, Dynamic load modelling and aggregation in power system simulation studies, in: Power System Conference, 2008. MEPCON 2008. 12th International Middle-East, 2008, pp. 270 –276. doi:10.1109/MEPCON.2008.4562351.

[12] A. Abdisalaam, I. Lampropoulos, J. Frunt, G. Verbong, W. Kling, Assessing the economic benefits of flexible residential load participation in the dutch day-ahead auction and balancing market, in: European Energy Market (EEM), 2012 9th International Conference on the, 2012, pp. 1–8. doi:10.1109/EEM.2012.6254645.

[13] Energy-pool, http://www.energy-pool.eu (March 2013).

[14] Smartplug, https://www.alertme.com/products/smartplug-1622.html.