An implementation of a Home Energy Management platform for Smart Grid

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***Abstract*—In recent years a great number of Smart Grid home monitor and control strategies have been proposed and many optimization algorithms were developed. However, many of them have only been tested by simulations, in part due to the absence of an open and versatile testing platform. We thus present a design and implementation of an open home energy management system platform. This implementation is based on Contiki OS, CoAP as application protocol, and IPv6 over 802.15.4 (6lowPAN) for communication. An optimization algorithm was implemented for a platform test. Experiments verified a good performance for the proposed architecture.**

***Index Terms*—energy measurement, smart grid, home energy management system, home energy controller, wireless home area network, demand response.**

I. Introduction

The development of telecommunications and information technologies has promoted the study of intelligent ways of managing the power grid. The widely known term Smart Grid refers to "the integration of power, communications, and information technologies for an improved electric power infrastructure that serves loads while providing for an ongoing evolution of end-use applications"[1]. This approach aims to further improve the grid management, allowing efficient use of energy resources and encouraging the incorporation of renewable energy.

The deployment of Smart Grid by the utility companies should integrate a Home Energy Controller (HEC) capable of controlling the appliances and loads in real time in order to optimize the home electric energy consumption.

Despite the fact that several home energy optimization strategies and algorithms were proposed, most of them have only been tested by means of computer simulations due to the lack of an open experimental platform which enables Home Energy Management System (HEMS) real testing. Besides, given that to date no HEMS have been widely adopted, we considered that designing and implementing an open HEMS platform would represent an opportune contribution.

In the present work we propose an architecture and implementation of a HEMS open platform, with a HEC capable of running energy optimization algorithms aiming to optimize the power consumption while maintaining user comfort. The proposed HEC also provides the user with consumption information that encourages energy efficiency.

The rest of the paper is organized as follows. In Section II we present the requirement analysis and the general architecture of the platform. Section III describes the details of the implementation. In Section IV we present the experiments performed. Finally Section V concludes the paper.

II. System Description

In a possible solution the electric utility exchanges data between it's billing system and the HEMS. This communication capability is essential for a great number of optimization algorithms which are based on the automatic energy price negotiation between the end user and the energy supplier [2], [3].

The HEMS platform is composed of a HEC and smart appliances. Since the last ones are still commercially very scarce and the aim of this work is to provide a research platform, smart plugs nodes were developed to integrate ordinary appliances to the system, adding the intelligence necessary to interact with the Home Area Network (HAN). The main function of these nodes is to measure the most important electrical parameters, such as voltage, current and power, and also control the appliances. To keep low the required bandwidth for the HAN communications, each node must pre-process the time-varying electrical signals acquired by the sensors in order to report just a summary to the HEC. We propose to aggregate to the system other class of nodes, capable of acquiring other environmental variables such as room and external temperature. The nodes should also be capable of receiving commands sent by the HEC, which are outputs of the local optimization algorithm, smart grid high-level decisions, or direct commands from the users. This means that a bidirectional communication system must be implemented in order to connect the nodes to the HEC.

Finally, a user interface is provided to facilitate data visualization, system status monitoring and appliance commands.

A. The Home Energy Controller (HEC)

The HEC constitutes the core of the platform. Although some basic measurement processing tasks are performed by the nodes, the optimization and negotiation algorithms will run entirely on the HEC, which must be capable of exchange information with the electric utility, and also communicate to the nodes through a HAN.

In summary, the main required features of the HEC are: i) capability to communicate to the electric utility, ii) capability to communicate to the smart appliances (nodes of the HAN), iii) enough processing power to run optimization algorithms, iv) user interface, and v) support of widely adopted programming languages to facilitate the development of optimization algorithms.

Based on [4] [5] [6] surveys on home energy optimization algorithms and a detailed study of a particular case [2], it can be stated that a standard computer is sufficient for the given purpose. In any case, the development of the HEC was made platform independent.

B. The nodes

The home appliances are connected to the nodes, which are capable of taking a set of measurements that will constitute an input to the optimization algorithm. They also need to be capable of taking control of the appliances upon command from the HEC. The nodes may measure, control, or both, depending on the particular case. We consider the following set of measurements: i) voltage supply, ii) current consumption, iii) power consumption, and iv) power factor.

High precision measurements are not a requirement and accuracy around 5% is considered to be sufficient. The measurements are intended for a residential sub metering perspective, and billing will not be based on them.

The measurement of some other variables might be required depending on the scenario. Because of this, the nodes must be designed in such a way that they support the easy incorporation of different types of sensors. Similarly, different kinds of actuators may be required for different control techniques and appliances. An on-off actuator allows low-scheduling the load and in many cases this control technique is sufficient [2], [4]. However if other kind of actuator is needed, the nodes must provide a standard interface to incorporate it.

C. The HAN communication system

The HAN communication infrastructure must provide a reliable, bidirectional data exchange path between the nodes and the HEC. There are several technologies available to achieve this, which could be classified in: i) wireless communication, ii) PLC communication.

It could be desired to install sensor nodes not attached to any home appliance or plug. Consider for instance lighting optimization; it could be useful to install light sensors in precise spots where there is not necessarily a plug available. Because of this limitation, wireless communication are the technology selected over PLC, since it provides a greater flexibility.

In order to define the main requirements for the WHAN (wireless HAN), taking into account the traffic requirements imposed by the application and the optimization problem, some algorithms were reviewed (e.g. [3]), in which if the energy variables are sent periodically and some control message is sent back by the HEC, the application can tolerate latencies on the order of 1 second.

III. Implementation

A. The HAN communication system

The amount of data to be exchanged between the nodes and the HEC is very low, so high data rate is not a requirement. On the other hand, low power consumption, support of mesh topologies and low memory footprint of the stack implementation are pursued. Because of this, low-rate wireless personal area networks (LR-WPANs) are considered the more suitable technology, leaving aside widely used technologies as Wi-Fi and Bluetooth.

In recent years multiple wireless communication technologies and protocols were developed. Many surveys on the different communication systems available for smart grid applications have been conducted. In [7] different suitable options are compared; ZigBee, 6LoWPAN, Z-Wave, INSTEON and Wavenis. ZigBee and 6LoWPAN share the fact that both use IEEE802.15.4 standard for lower layers, and in both cases the protocol specification is open. This is not true for the rest of the mentioned options. Because of this, the decision was narrowed down to a choice between ZigBee and 6LoWPAN. ZigBee has been widely used in the last years and offers a very good industry support [8]. The 6LoWPAN is an adaptation layer enabling IPv6 over IEEE802.15.4 by header compression on low-power embedded devices. 6LoWPAN has important advantages over Zigbee for this application, such as: i) native IPv6 support with no need of a protocol converter to connect to Internet, ii) very light implementation available with Contiki software platform in terms of power processing and memory footprint (Contiki is described in more detail in Section III-B), iii) support of mesh topologies with sleepy routers, iv) open specification (IETF RFC 6282) with no license required, and v) great hardware compatibility (IEEE802.15.4 radios).

Due to these reasons, IPv6 over 6LoWPAN was chosen as the basis for the HAN communication.

However, 6LoWPAN doesn't solve all the requirements by itself; a meshing mechanism and application protocol needs to be used on top of it. RPL routing protocol is the most widely adopted meshing strategy over 6LowPAN. It's been succesfully used and tested in the context of Smart Grid and applications related to our working area [9], [10], [11]. RPL is an IETF standard for IPv6 routing in low-power wireless sensor networks [12]. It's a very flexible protocol based on a tree-oriented strategy in which the topology is automatically built by the nodes, based on different metrics criteria, such as minimum hop-count or some link quality indicator.

As for the application protocol, native IPv6 support of 6LoWPAN allows usage of REST (Representational State Transfer) based protocols using a client-server architecture. In the last years the CoRE working group of IETF has developed a very light REST based protocol called CoAP [13], which is already implemented in Contiki and offers a very easy, open and flexible architecture which makes it ideal for this application. In this REST architecture, information is available as resources. Applications exchange representations of these resources using methods such as PUT, POST, GET and DELETE. For each resource, there will be typically one server and one or more subscribers, who are aware of that resource's updates. This allows the applications to subscribe only to the resources of interest for them instead of receiving all the data on the network.

Summarizing, the stack for the HAN communication system will be: i) CoAP, ii) IPv6/RPL, iii) 6LoWPAN, and iv) IEEE 802.15.4.

B. Hardware and software node implementation

The nodes are based on the Zolertia Z1 hardware modules. The Z1 module is equipped with the second generation of the widely adopted MSP430 microcontroller (MSP430F2617) and a CC2420 radio transceiver. It supports the Contiki OS.

Contiki OS is a lightweight open source operating system, designed for memory-constrained devices, and was the first operating system to provide IPv6 connectivity for wireless sensor networks [14]. Among the main characteristics of this operating system, we highlight these as particularly important for the project: i) tested communication modules, including technologies as 6LoWPAN, RPL and CoAP, ii) open source, iii) small memory footprint, and iv) supported by various different hardware platforms.

C. Measurement and command

As mentioned before, one of the key features of a smart grid system is the capability of providing power measurement information. This information could be used by the HEC to take automatic decisions, and also help the user to understand the impact of their behavior to optimize the energy consumption [15].

A signal conditioning board was designed and constructed to measure the appliance consumption. This board senses the current and voltage of the appliance which are properly adapted to be sampled by an ADC of the microcontroller in the Z1 module. It includes three differential amplifiers for signal conditioning, and an DC power supply.

Figure 1 shows a block diagram of the implemented circuit.

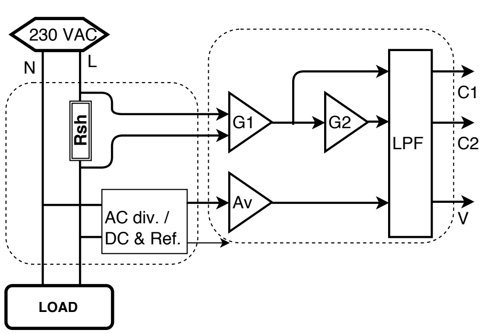

Fig. 1. Acquisition board diagram.

A shunt resistor is used as a current sensor, and its output voltage is amplified in two stages (G1 and G2). Both current signals are fed to the microcontroller, and the process running on the Z1 mote is responsible for selecting the most convenient one. This strategy helps to improve the dynamic range of the current signal. The voltage signal is adapted to the source voltage of the Z1 ADC by means of a voltage divider and a differential amplifier with gain Av=0.01 V/V. A rectifier circuit and a voltage regulator produce a DC power source for the acquisition and sampling board, and a DC voltage reference set to maximize the output voltage excursion of the signals.

A calibration is necessary in the acquisition circuit to obtain the precise value of the gain on each signal, and the phase shift introduced by the board. The voltage and current signals are acquired by 12-bit SAR ADCs and saved in three buffers of size N. The root mean square of the current and voltage are computed as:

$$I_{rms} = \sqrt{\frac{1}{N} \cdot \sum_{k=1}^{N} (I[k])^2}, \quad V_{rms} = \sqrt{\frac{1}{N} \cdot \sum_{k=1}^{N} (V[k])^2} \quad (1)$$

The active and reactive power are calculated as follows:

$$P = \frac{1}{N} \cdot \sum_{k=1}^{N} V[k].I[k], \quad Q = \frac{1}{N} \cdot \sum_{k=1}^{N} V[k].I[k - \frac{N}{4}] \quad (2)$$

A sampling frequency of 8KHz is used for the signal acquisition. Samples representing one and a half cycle of the 50Hz wave are stored. A simple first order RC anti-aliasing filter was included to pass frequencies up to the 10^{th} harmonic.

Other important requirement of a HEMS is the capability of controlling the appliances. In this first implementation, only on-off commands are supported. This is implemented by means of a relay board, capable of switching the power of the appliance, according to the command sent to the node by the HEC. A Phidget Dual Relay board was used to implement this function.

D. The HEC

As was stated before, the HEC is the platform's core and must intelligently fill the gap between power utilities and load actuators/sensors by performing optimization routines. A Raspberry Pi Model B+ (RPi) was chosen as a Single Board Computer to perform this task. The RPi is operated at 700 MHz with the single-core ARM1176 and 512 MB of RAM. This cheap, portable and low power computer primarily uses Linux-kernel-based operating systems like Raspbian. The RPi is connected to the WHAN through a Z1 module programmed with the border router application (supplied with the standard distribution of Contiki), and to Internet through an ethernet port or a USB WIFI (IEEE 802.11) adapter.

In order to facilitate the integration of optimization algorithms on the platform, a Python library with all the basic communication and processing functions was developed. This library provides a basic API, implementing functions such as: transmission of messages towards the WHAN using the Python CoAP library *aiocoap*, communication with the electric utility to get price information, and data management functions for sending the data into a web user interface. The implementation of the user interface for consumption visualization and commanding the appliances was based on the open source web-app *Emoncms*.

As an example of use of the API, a user script was developed above it. This script uses the mentioned library and its communication functions to exchange data with several nodes. It also manages a database with historical measurement data, system events, user profiles and runs the user's home power optimization routine, which generates the automatic control messages to be sent to the nodes.

IV. Experiments

The nodes were tested and calibrated in laboratory. The on/off command was not very challenging and didn't present any problems. As for the energy measurement, we obtained errors below 5% as expected. Although this could be improved in next generations of the system, it does not prevent its use in the current implementation, since the energy measurement is mainly intended to orient the user towards efficient energy usage and not for billing purposes.

The platform was then installed in a typical size home, and a good communication performance was verified. In spite of the negative impact of obstacles like walls on the direct link paths, a good performance was achieved thanks to the multi-hop network topology provided by RPL. The latencies experimented on point-to-point links were always lower than 200 ms, but when the distances and the amount of obstacles were increased a multi-hop topology was needed. The retransmission of the packages on up to four nodes using RPL increased the latency to 500 ms, remaining acceptable for the application, but CoAP packet loss was affected, getting increased from 5% in the LOS case to 15%.

In order to test the whole platform's performance, a simple optimization algorithm was implemented. Due to Electric Water Heater big participation in global home consumption and shifting load capacity, this load was particularly taken account by this test optimization routine. A 6-step load scheduling algorithm proposed in [2] was implemented. The routine outputs are time discrete ON/OFF states which are transmitted to local actuators.

V. Conclusions

Open source well known technologies, as CoAP, IPv6 with 6LoWPAN and RPL, IEEE802.15.4, and Contiki OS, were integrated in the implementation of a Smart Grid HEMS open platform. The main goal of this work was the development of an open platform that would allow testing HEM optimization methods and algorithms. Finally, a simple optimization algorithm was developed as a test case in order to evaluate and show the platform's capabilities.

A Python library providing basic communication and processing functions was developed. This library is provided to the user as an integration API to facilitate the incorporation of optimization algorithms.

A low-cost SBC was used for the implementation of the HEC, but the development was made platform-independent. The controller could run on a more powerful computer, in case that the optimization algorithm requires more processing power.

The selected platform for the measurement and command nodes, Zolertia Z1, proved to have sufficient processing capabilities to make the power and RMS calculations. However more RAM and flash will be required if more complex processing tasks need to be implemented. The achieved measurement accuracy is enough for orientation of the user towards efficient energy usage, and could be improved in next generations of the system.

The testing algorithm showed that the platform fulfils the original objectives, and the use of switch relays as control technique was shown to be sufficient to optimize the energy consumption on many appliances, and particularly an Electric Water Heater.

The communication technologies used were shown to be reliable and adequate for the purpose, and the processing capabilities of the HEC, although not highly demanded by the tested algorithm, proved to be highly satisfactory.

References

[1] "IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads," Tech. Rep., 2011.

[2] P. Du and N. Lu, "Appliance Commitment for Household Load Scheduling," *Smart Grid, IEEE Transactions on*, vol. 2, no. 2, pp. 411–419, Jun. 2011.

[3] G. Xiong, C. Chen, S. Kishore, and A. Yener, "Smart (in-home) power scheduling for demand response on the smart grid," in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*. IEEE, Jan. 2011, pp. 1–7.

[4] M. R. Alam, M. St-Hilaire, and T. Kunz, "A survey on cost saving methods for smart grids," in *Smart Energy Grid Engineering (SEGE), 2013 IEEE International Conference on*. IEEE, Aug. 2013, pp. 1–7.

[5] Y. W. Law, T. Alpcan, V. C. S. Lee, A. Lo, S. Marusic, and M. Palaniswami, "Demand Response Architectures and Load Management Algorithms for Energy-Efficient Power Grids: A Survey," in *Knowledge, Information and Creativity Support Systems (KICSS), 2012 Seventh International Conference on*. IEEE, Nov. 2012, pp. 134–141.

[6] R. Deng, Z. Yang, M.-Y. Chow, and J. Chen, "A Survey on Demand Response in Smart Grids: Mathematical Models and Approaches," *Industrial Informatics, IEEE Transactions on*, vol. 11, no. 3, pp. 570–582, Jun. 2015.

[7] C. Gomez and J. Paradells, "Wireless home automation networks: A survey of architectures and technologies," *Communications Magazine, IEEE*, vol. 48, no. 6, pp. 92–101, Jun. 2010.

[8] A. I. Peizhong Yi and C. Zhou, "Building automation networks for smart grids," *International Journal of Digital Multimedia Broadcasting*, vol. 2011, no. 2, Apr. 2011.

[9] E. Ancillotti, R. Bruno, and M. Conti, "The role of the RPL routing protocol for smart grid communications," *Communications Magazine, IEEE*, vol. 51, no. 1, pp. 75–83, Jan. 2013.

[10] H. Ali, "A performance evaluation of rpl in contiki," Master's thesis, Swedish Institute of Computer Science (SICS), Sweden, School of Computing, Blekinge Institute of Technology, SE – 371 79 Karlskrona, Sweden, 2012.

[11] N. Tsiftes, J. Eriksson, and A. Dunkels, "Low-power wireless IPv6 routing with ContikiRPL," in *Proceedings of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks*, ser. IPSN '10. New York, NY, USA: ACM, 2010, pp. 406–407.

[12] T. W., "RPL: IPv6 routing protocol for Low-Power and lossy networks," Internet Requests for Comment, RFC Editor, Fremont, CA, USA, Tech. Rep. 6550, Mar. 2012.

[13] C. Bormann, A. P. Castellani, and Z. Shelby, "CoAP: An application protocol for billions of tiny internet nodes," *Internet Computing, IEEE*, vol. 16, no. 2, pp. 62–67, Mar. 2012.

[14] A. Dunkels, J. Eriksson, N. Finne, F. Osterlind, N. Tsiftes, J. Abeille, and M. Durvy, "Low-power ipv6 for the internet of things," in *Networked Sensing Systems (INSS), 2012 Ninth International Conference on*, June 2012, pp. 1–6.

[15] S. Aman, Y. Simmhan, and V. Prasanna, "Energy management systems: state of the art and emerging trends," *Communications Magazine, IEEE*, vol. 51, no. 1, pp. 114–119, January 2013.