Characterization and breakdown of the electricity bill using custom smart meters: a tool for energy-efficiency programs.

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***Abstract*—** Understanding and monitoring the electrical energy use is fundamental to encourage consumers and small business owners to implement energy-efficiency measures and, therefore, to cut their energy bills significantly. This works presents the design, development and implementation of an electrical energy monitoring sensor network which can be easily installed to measure and monitor the energy use of every appliance in a house, presenting to the consumer a detailed report of the energy spent by each electrical device (TV, lights, showers, etc.). The measuring units and a coordinator form a wireless network, which is capable of measuring the electrical energy and recording the data of each home appliance in the flash memory of the coordinator. The data stored in the coordinator is sent (via a wireless connection) to a computer where the analysis of the data is performed and a detailed report of the energy breakdown is presented.

***Keywords*—**PLC, Power meter, Sensor network, ZigBee.

I. Introduction

REDUCING energy consumption and eliminating energy wastage are among the main goals of every country that has made commitments under the Kyoto Protocol.

These countries recognize that the world climate is changing and that it is necessary to reduce greenhouse gas (GHG) emissions.

According to [1], the main source of greenhouse gases due to human activity is burning of fossil fuels.

Studies like [2], [3] and [4] show how it is possible to generate electricity from renewable energy source sources other than burning fossil fuel. Unfortunately, those technologies are not widely spread yet.

BP Statistical Review of World Energy June 2009 [5] shows that in 2008, total worldwide energy consumption was 474 exajoules (474×10^{18} J) with 80 to 90 percent derived from the combustion of fossil fuels.

We understand that if this scenario does not change, it can lead us to an unpleasant future. A proposal to help changing this scenario is the promotion of energy-efficiency programs.

Investigate the way people make use of electrical power in their residences is a good step to get to know how to improve its usage.

Data collected by the largest electricity distribution company in Brazil, AES Eletropaulo S.A. [6], show that many consumers have not a good picture of how they spend the electricity they pay for. They sometimes complain about their high electricity bills, but usually cannot indicate why and what caused the large energy use.

This paper presents the development of a system composed by a sensor network of wireless smart energy meters that presents the detailed characterization and breakdown of the electricity bill, offering a powerful tool to encourage them to implement energy-efficiency measures and, consequently, reduce their electricity wastage.

With this detailed information in hands, consumers can understand how much they spend with every single electrical device in a house and, therefore, take measures to reduce their impact on the electricity bill and also on the environment.

II. Objective

In order to be practical, the developed the sensor network formed by wireless smart energy meters has to be simple to install and easy to be deployed in a residence or small business, without requiring any changes in the original electrical wiring.

The system should be able to measure the amount of energy consumed by every electrical device in the building over a period of 10 to 15 days and store the information.

After the acquisition period the system should provide a detailed report identifying every monitored device, their energy consumption, the cost of the energy spent and also a projection for a period of a month.

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III. Applications

The developed system is planned to be offered as a service by the electricity companies.

It is intent to be offered to customers who want to know better how they use the energy they are paying for and also in energy-efficiency programs

Those are the biggest potential candidates for using the service, although the system could be also commercialized to customers who want to keep tracking their energy consumption permanently.

IV. Elements of the System

The system is composed by five elements: a coordinator, a displaying-processing unit (DPU) and three types of smart energy meters: one for devices that can be plugged to a power outlet, one for heavy loads and/or devices that are wired directly to the AC mains and another for lightning sets.

The main element of the system is the coordinator. It receives the information from the network and keeps it for the DPU to retrieve.

The DPU is basically a PC that connects to the wireless network as an end device, and is responsible for retrieving the information stored in the coordinator, processing it and displaying to the user in a user-friendly report. The DPU does not need to be online during all the acquisition period. It can access the coordinator at the end of the acquisition period to retrieve the information stored.

The smart energy meters are responsible for the data acquisition and, as nodes of the wireless network, also perform the function of routing devices.

V. Smart Meters Modules

To measure and monitor the energy consumption of all electric devices in a house without any changes in the original electrical wiring installation, it was necessary to develop three different types of smart energy meters.

A. Power outlet adaptor smart meter

This smart energy meter is to be employed to measure and monitor the energy consumption of every device that can be plugged to a power outlet.

The home appliance power cord is simply plugged to the smart energy meter device, which has a plug to be connected into the AC power outlet, as shown in Fig.1.

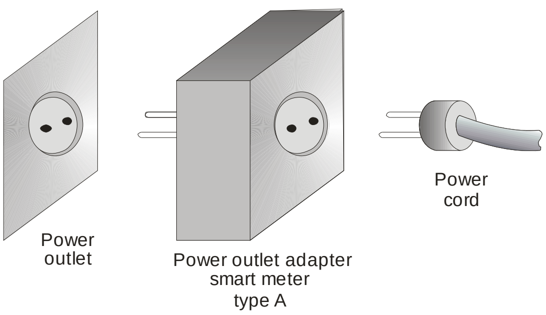

Fig. 1 Power outlet adaptor smart meter installation scheme.

It is based on the energy meter integrated circuit AD71056 [8] from Analog Devices. Fig. 2 shows the functional block diagram of the AD71056, that measures the amount of energy consumed and has an output which is a frequency proportional to the energy being measured.

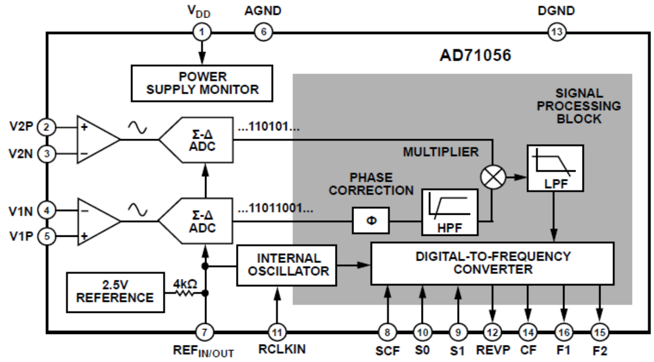

Fig. 2 AD71056 functional block diagram.

Fig. 3 shows the block diagram of the Power outlet adaptor smart meter.

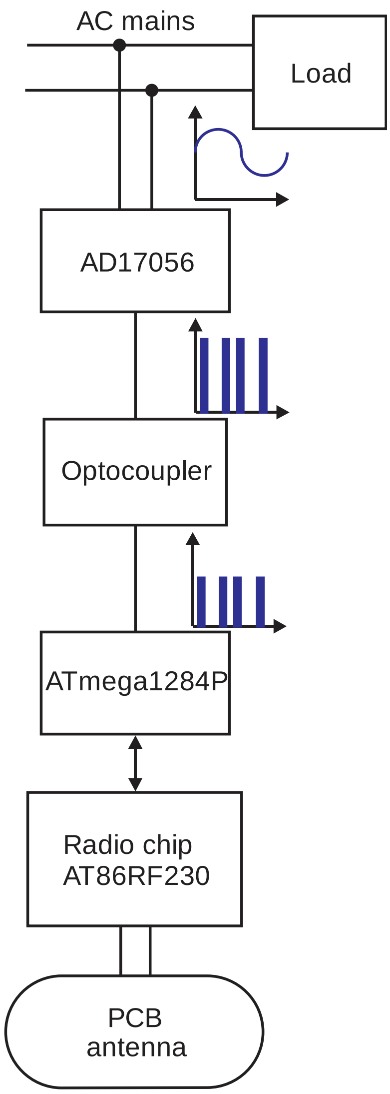

Fig. 3 Block diagram of the Power outlet adaptor smart meter.

As shown in Fig. 3, the pulse train from the AD71056 goes to the microcontroller passing through an optocoupler that isolates the energy metering IC from the microcontroller and guarantees that the microcontroller will receive a 3V3 signal instead of a 5V signal that comes from the energy metering IC.

The ATmega1284P microcontroller in the smart energy meter counts those pulses and, every 5 minutes, send the total number of pulses to the coordinator.

Fig. 4 shows the Power outlet adaptor smart meter at the first implementation of the PCB.

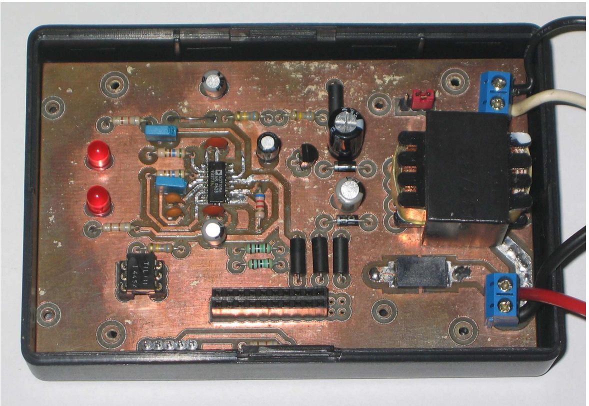

Fig. 4 First implementation of the Power outlet adaptor smart meter PCB

B. Clamp smart meter

This smart meter make use of a current clamp to measure the current on electrical devices that are wired directly to the AC mains, as it is the case of showers in Brazil, and the amount of time it is kept on.

The clamp works as a current transformer in which the primary is the wire on which the clamp measures the current. The secondary is the coil wrapped around the core and the core of the clamp behaves like the core of the transformer. As in the clamp the number of turns in the secondary is much higher than in the primary, the induced current in the secondary is much smaller than the primary current, allowing measurement to of high current values.

By allowing the induced current in the secondary to pass through a resistance, we have a voltage proportional to the induced current that is also proportional to current in the primary.

This voltage signal is then transformed to RMS and read by the ADC at the microcontroller.

Certainly, by acquiring only the current and not the voltage on these devices, the energy has to be calculated. That is done by the network coordinator, when it receives the data sent by the meter module. To calculate the energy accurately, the AC voltage is measured in one A/D converter available in the coordinator.

Fig. 5 shows the Clamp smart meter at the first implementation of the PCB and Fig. 6 shows a block diagram of that device.

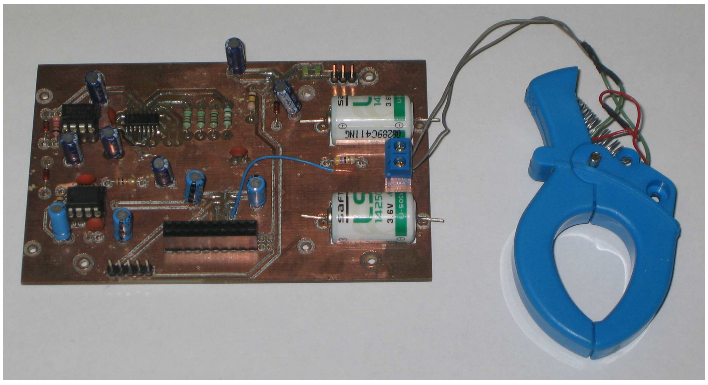

Fig. 5 First implementation of the Clamp smart meter PCB

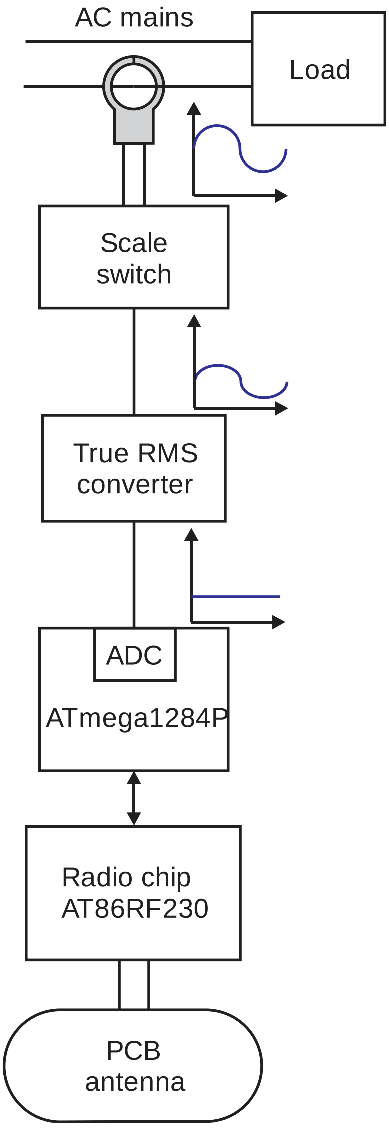

Fig. 6 Block diagram of clamp smart meter.

One important thing regarding the clamp as a current transformer is that it has to have a very linear output to avoid errors in the measurement.

The Fig. 7 shows the result of the linearity test of the clamp used in the project and the Fig. 8 shows the linearity test that also as used to choose the circuit mode of the clamp.

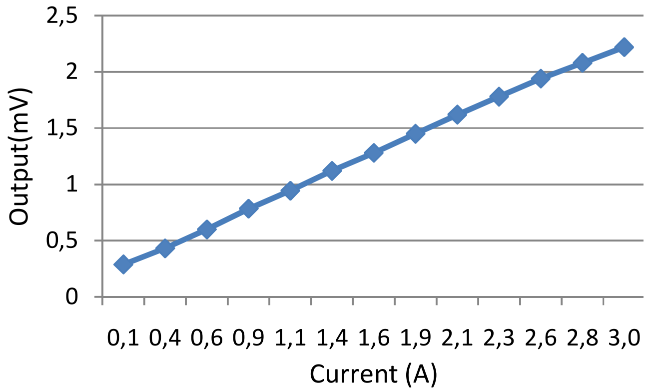

Fig. 7 Result of the linearity test of the clamp used in the project

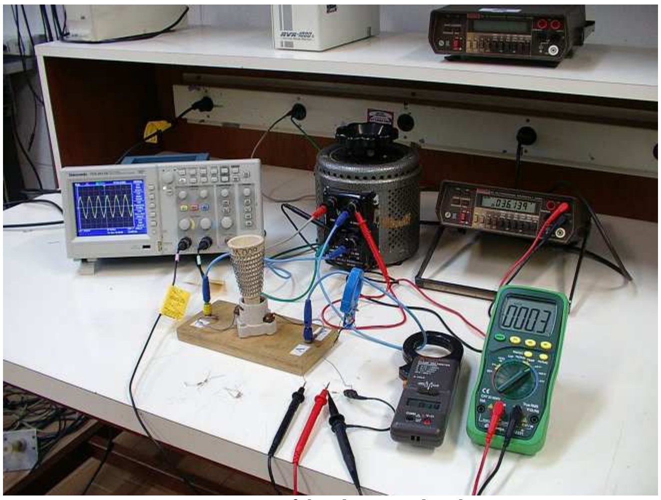

Fig. 8 Linearity test of the clamp used in the project

C. Light smart meter

This energy meter is used to measure and monitor the energy consumption of lightning devices which are not accessible by the clamp meter (for example, fluorescent lights in ceiling mounting fixtures). This smart energy meter uses a photodiode to detect the light status (on or off), and when the photodiode detects that a light was turned on, the microcontroller is woke-up and starts to measure the amount of time that the light is kept on.

Fig. 9 shows the installation scheme of this smart meter. The photodiode is fixed at the end of a flexible straw that should be aimed at the lighting set. It is necessary one meter module for each lighting set that is commanded by one switch.

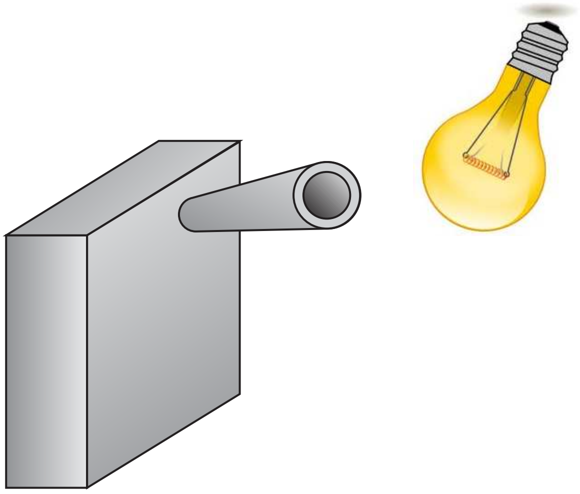

Fig. 9 Installation scheme of light smart meter

During the system installation/programming, the power of all lights that are monitored by one photodiode is stored in the DPU. Thus, the energy consumed by the set of lights is easily calculated by the software.

Fig. 10 shows the block diagram of the Light smart meter and Fig. 11 shows the Light smart meter at the first implementation of the PCB.

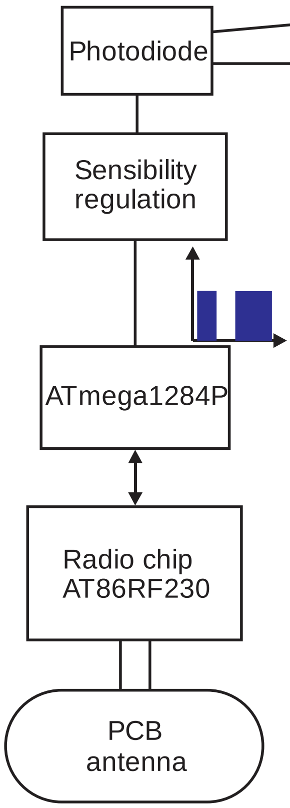

Fig. 10. Block diagram of the Light smart meter

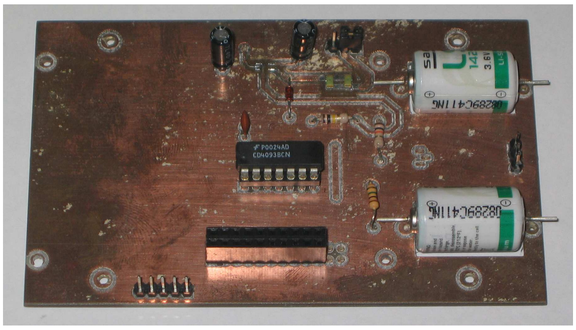

Fig. 11 First implementation of the Light smart meter PCB

D. The coordinator

The coordinator is responsible for storing the information sent by the smart energy meters and to sustain the wireless network.

It also performs an AC voltage measurement every 5 minutes and stores the mean value in order to calculate the energy measured by the Clamp smart meter.

It is basically composed by the same core of the smart meters, pretty similar to the Clamp smart meter, plus a PLC modem, and it is not battery powered.

Fig. 12 shows the Coordinator at the first implementation of the PCB. And Fig. 13 shows the block diagram of the Coordinator.

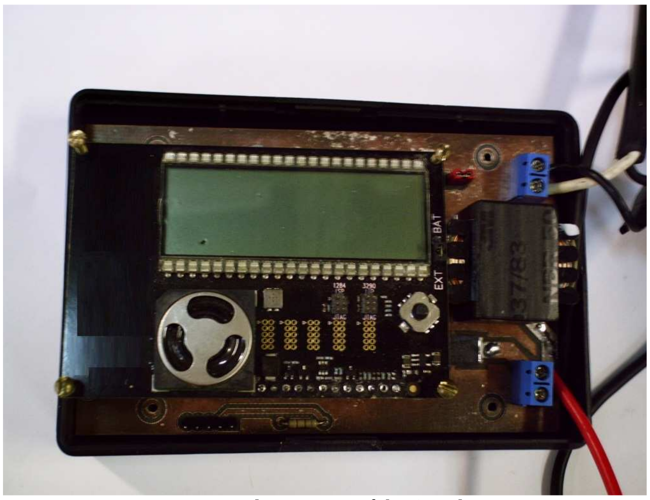

Fig. 12 First implementation of the Coordinator

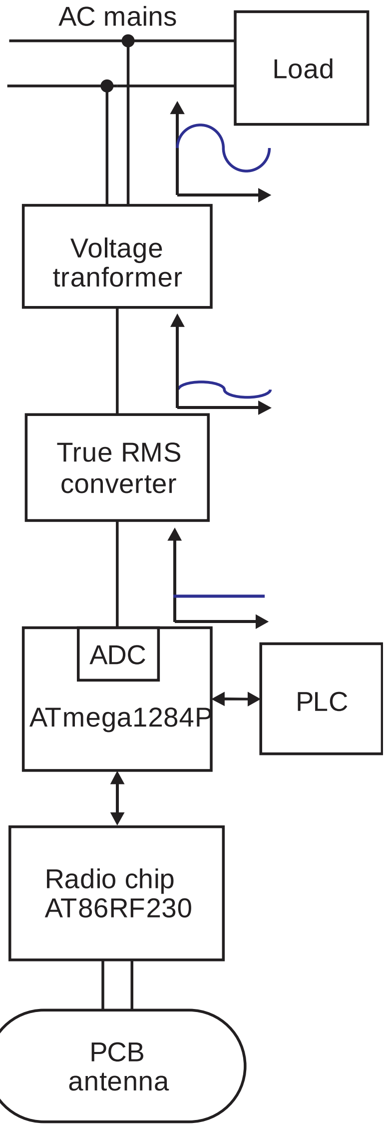

Fig. 13. Block diagram of the Coordinator.

E. The smart meters core

In the first version of the system, for testing the concept, the smart energy meters where developed based on the RZ Raven development kit from AVR [7].

In this case, the microcontroller ATmega1284P was used to acquire the data from the sensors and also send it to the network coordinator, through the wireless system.

The main core of the wireless smart energy meter is shown in Fig. 14.

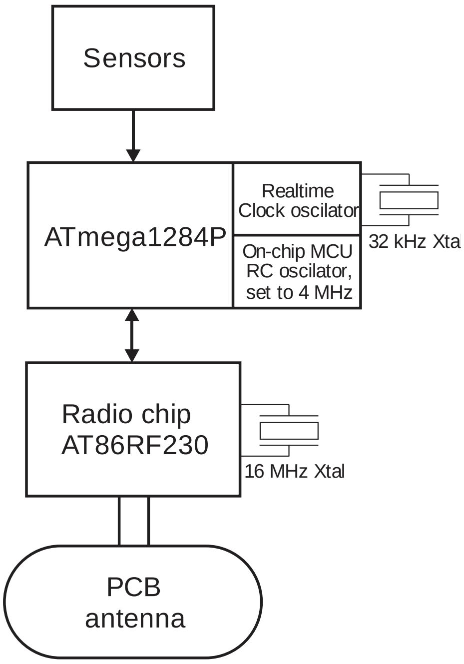

Fig. 14 Smart meters main core.

VI. Wireless Sensor Network

The smart energy meters form a wireless network based on the ZigBee [9] protocol, which is very appropriate for the application, because:

- It has been designed to provide low power consumption;
- The physical layer was designed to accommodate the need for a low cost yet allowing for high levels of integration. The use of direct sequence allows the analog circuitry to be very simple and very tolerant towards inexpensive implementations.
- The media access control (MAC) layer was designed to allow multiple topologies without complexity. The power management operation doesn't require multiple modes of operation. The MAC allows a reduced functionality device (RFD) that needn't have flash nor large amounts of ROM or RAM. The MAC was designed to handle large numbers of devices without requiring them to be "parked".
- The network layer has been designed to allow the network to spatially grow without requiring high power transmitters. The network layer also can handle large amounts of nodes with relatively low latencies [10].

As also experienced by [11] and [12], this protocol fits perfectly the needs of a sensor network.

As well as the Coordinator, the Power outlet smart energy meters perform the function of routers, by connecting end devices to other routers and to the coordinator. These devices are powered from the mains and have little restriction to power consumption, although they were designed to be low power.

The Clamp smart meter and the Light smart meter works as end devices in the wireless network. That is because they are battery powered devices and were developed to be as low power as possible in order to obtain a long battery life. The current drained by a router would reduce the battery life, increasing the operational costs of the system.

The DPU connects to the ZigBee network as an end device by an USB dongle attached to the PC.

In Fig. 15 it is shown an illustration of the wireless network.

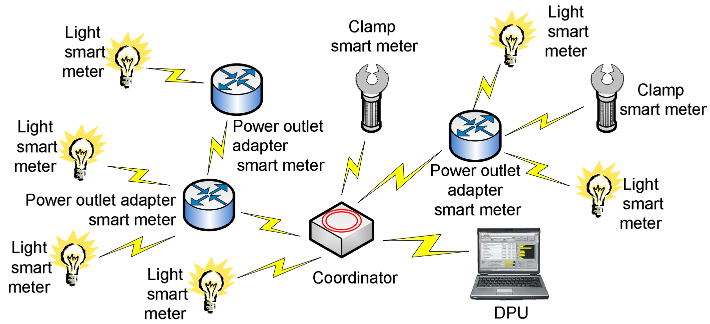

Fig. 15 Network.

VII. PLC

Sometimes, due to the characteristics of the local being monitored or due to the building structure/construction, it is difficult to establish the communications between some end devices and the coordinator or a router. For example, in an industrial installation with two nearby buildings which are enough far away one from the other that the ZigBee wireless network cannot link one building to the other.

In some cases a power outlet adapter can be placed between the two buildings, in order just to make a bridge to those distant end devices.

However, in cases where this strategy cannot be used, a second ZigBee network can be assembled and a connection link between the networks must be established.

In this project it was developed an architecture where each ZigBee network (two or more) are connected via their respective coordinators, which send/receive data to each other using a serial protocol implemented with a Power Line Communication – PLC link.

Just like any other device in the network, the slave coordinator will send the data to the master coordinator every five minutes. Thus, the master coordinator will concatenate all the data in only one point, so that the DPU can retrieve it at once.

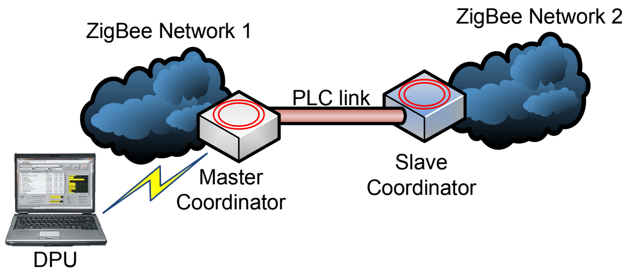

Fig. 16 PLC linking two ZigBee networks

A power line is used for transmitting 50 or 60 Hz signals but was not designed to convey high frequency signals. A power line channel is somewhat like a wireless channel - both of them suffer from noise, fading, multi-path and interference. Power line noise is produced by the operation of electrical devices. Fading, multi-path and interference are caused by the imperfection of power line channels [13].

Typical attenuation characteristics in power line channels are given in [14]. The author reports that even when all devices are unplugged, the noise still persists and this drastic variation of attenuation is hostile to power line communication. Furthermore, the Federal Communications Commission (FCC) also limits the available bandwidth for communication purposes. In compliance, the usable bandwidth in standard is 25MHz. An extensive study of the power line channel characteristics and design issues is given in [15].

To avoid data loss and prevent communication problems with the PLC link, this project has focused on data protection over the PLC link, limiting the data rate to 4800 bps.

VIII. Data Acquisition

All the information acquired by the smart meters is sent to the coordinator at every five minutes.

The power outlet adapter smart energy meters send the amount of energy consumed already calculated and processed while Clamp smart meters send the mean value of the electrical current along with the time the device was kept on. The light smart energy meters send only the amount time the lightning device was turned on.

Every time the coordinator receives data from a power outlet adapter smart energy meter or a light smart meter, it saves that data directly to its memory. When the data comes from a clamp smart energy meter, the coordinator also measures the mean value of the AC voltage and uses it to process the amount of energy consumed before saving this data.

The light smart meter sends only the amount of time the lightning set was kept on. To calculate the energy the set has drawn it is necessary to feed the DPU with the power of each lightning set.

At the end of the monitoring period the DPU can retrieve the information stored in the coordinator.

IX. Reporting Software

The reporting software is the software that goes in the DPU that process the data retrieved from the coordinator and then display it in an user-friendly report.

It is basically composed by two control tabs.

The first tab is the installation tab and it is used at the deployment of the smart meters

This tab allows the user to fill in all the names of the monitored devices matching them with the ID of the smart meters that is going to monitor the electrical devices, as well as the type of the smart meter and the nominal power in case of a type C smart meter, as shown in Fig. 17.

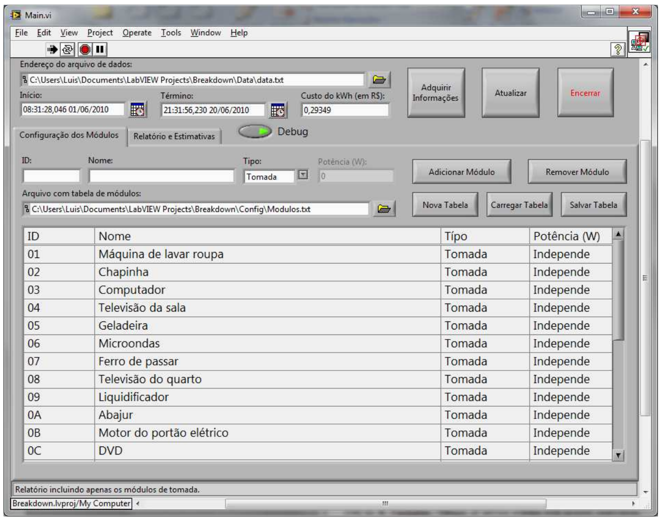

Fig. 17 Reporting application, first control tab.

By the time the reporter retrieves the information from the coordinator, it still has to process the amount of energy consumed by the lighting devices.

The software uses the information filled in the first tab to process that information.

The second tab, as shown in Fig. 18, is the report itself. It presents to the customer all the electrical appliances with their respective consumption, and their impact on the electricity bill. It also calculates an estimative of the monthly electricity costs.

The list can be filtered by smart energy meter types, and a graphic at the right shows the percentage of consumption that each electrical device is responsible for. This graphic can be switched between energy (in kWh) and cost.

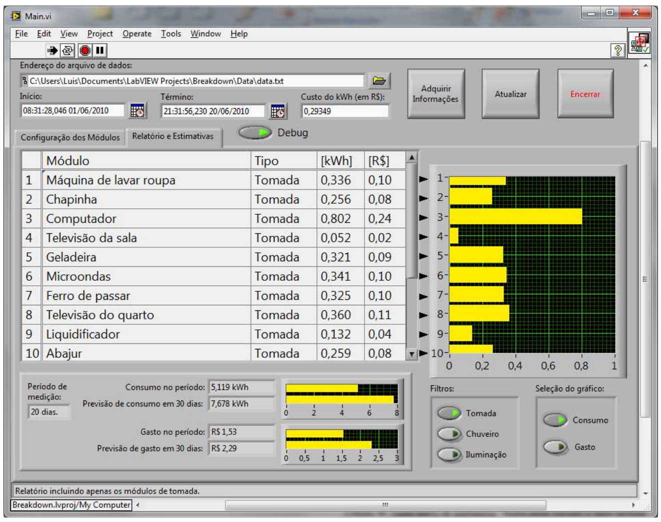

Fig. 18. Reporting application, second control tab.

X. Conclusion

This paper presents the development of a hybrid network sensor system able to measure and characterize the breakdown of the electricity bill using custom wireless smart energy meters.

Although the accuracy of the energy measurements performed with the proposed system is reduced due to the use of the clamp and light smart energy meter, the gains in installation and deployment simplicity were key elements to the success of the project.

The fact that the clamp and the light smart energy meters present errors in the calculated energy which are up to 4.5%, depending on the AC voltage fluctuations of the residence under test, is not a critical issue. This accuracy is adequate to present an excellent estimation of the energy breakdown of the electricity bill, showing the customers how and what can be done to reduce their electricity costs.

The hybrid architecture developed (wireless+PLC) proved to be an important feature of the system, since it can be used in virtually any installation, since there is no theoretical limit for the number of ZigBee networks that can be connected via the PLC link.

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