MONERGY: ICT solutions for energy saving in Smart Homes

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Technical Report

System architecture and test bed release

Definition Systemarchitektur und Testbed

Definizione dell'architettura di sistema e del banco di prova

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Abstract

The main goals of the MONERGY project are:

- To increase the inter-regional knowledge of technologies and solutions in the field of Smart Grids.
- To promote the research and the innovation in ICT by targeting solutions that have an impact on the reduction of energy-consumption within houses by considering the peculiarities of the Friuli Venezia Giulia and Carinthia regions.

Within MONERGY, the objectives of WP4 (entitled *Hardware Architecture Analysis and Integration*) are:

- To provide a hardware validation platform that will allow for (a) the validation of the research results of WP3, and (b) carrying out the research activity of WP5.
- To provide the guidelines for the definition of the hardware architecture elements that would enable the most comprehensive set of functionalities for home energy monitoring systems.
- To define the fundamental limits, from a communication point of view, of radio and power line devices that can be exploited for monitoring and controlling the in-home appliances.

The overall goal of this research is to lay ground for a ”plug-and-play” architecture that relieves the user from tedious set-up and configuration tasks.

This deliverable presents the work carried out within WP4. In particular, it gives a review of the state-of-the-art home energy management systems (HEMSs), then it presents the HEMS solution developed within MONERGY. It has been installed in 9 households of Friuli Venezia Giulia (Italy) and Carinthia (Austria) to monitor the energy consumption of inhabitants. The measurement campaign together with the GREEND

dataset that is being derived from it are also presented. Experimental hardware and software developments that solve some of the drawbacks of existing HEMS are finally presented.

Executive summary

This deliverable includes the results of the research carried out within WP4. In particular, the following topics are addressed.

- **Home energy management systems: state-of-the-art** - A description of the HEMSs that are commercially available is given. Their hardware (HW) limits are highlighted.
- **Monergy HEMS** - The HEMS developed within MONERGY is presented. It is composed of smart plugs (SPs) and of a smart home gateway (SHG). The SHG gathers power consumption data from smart plugs via Zigbee connection. Then it sends these data to a web server where energy consumption data can be visualized.
- **The monitoring campaign and the GREEND dataset** - The MONERGY HEMS has been installed in 9 households in Friuli Venezia Giulia and in Carinthia. The power consumption of 9 electrical appliances is monitored with intervals of one second within each household. The GREEND dataset, that represents the dataset that is being obtained within the monitoring campaign together with the description of the monitoring campaign are presented. The GREEND dataset will be used in WP5 to derive usage models of energy consumption and analogies/differences between energy consumption patterns in Italy and Austria.
- **Experimental Hardware and Software** - Some solutions to solve the HW/software (SW) limits of existing HEMSs are presented. In particular, a gateway Zigbee-power line communication (PLC) has been developed to solve coverage problems. Furthermore, in order to monitor aggregate energy consumption within the household, a sub-meter that can be mounted on a DIN-RAIL module has been developed . Finally, a graphical user interface (GUI) that is suitable to visualize the energy consumptions of electrical appliances connected to the SP on a small touch screen display that can be mounted on the MONERGY SHG is presented.

Contents

List of Acronyms

6LowPAN IPv6 over low-power wireless PAN

ACK acknowledgement

AMR automatic meter reading

APM aggregate power meter

API application programming interface

ARIB Association of Radio Industries and Business

BB broadband

BPSK binary phase shift keying

CA collision avoidance

CAR Carinthia

CDF cumulative distribution function

CENELEC European Committee for Electrotechnical Standardization

CSMA carrier sense multiple access

DB data base

DR demand response

DSSS direct sequence spread spectrum

DVD digital video player

DSO distribution system operators

EMS energy management system

FCC Federal Communication Commission

FSK frequency shift keying

FVG Friuli Venezia Giulia

GFSK Gaussian FSK

GUI graphical user interface

HA home automation

HAN home area network

HEMS home energy management system

HG home gateway

HW hardware

ICT information and communication technologies

IDE integrated development environment

IETF Internet Engineering Task Force

IP Internet protocol

ISM industrial, scientific and medical

ISR in-system programmer

ITU International Telecommunication Union

JSON javascript simple object notation

MAC medium access control

MCU micro controller unit

NB narrow-band

NILM non-intrusive load monitoring

OFDM orthogonal frequency division multiplexing

PAN private area network

PER packet error rate

PHY physical

PL power line

PLC power line communication

PSD power spectral density

QPSK quadrature phase shift keying

RCCB residual current circuit breaker

REST representational state transfer

SCADA supervisory control and data acquisition

SDK software development kit

SEP smart energy profile

SG smart grid

SHG smart home gateway

SOHO small office home office

SP smart plug

SW software

TV television

WG working group

W2W wireless to wireline

WLAN wireless local area network

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Section 1

Introduction

The progressive deployment of energy generators from renewable energy sources, such as photovoltaic and wind turbines, as well as the diffusion of electric vehicles, yields instability in the offer and demand of energy in the grid. In order to control the amount of energy required by their customers, utilities are getting progressively involved in demand-side programs. These programs include the promotion of efficiency and energy conservation, by raising the awareness of customers towards the footprint of their daily activities. Feedback mechanisms, e.g., consumption information, can be used to this end. The increase in awareness together with the adoption of time changing tariffs is a typical approach followed to realize demand response (DR) programs, i.e., the users shift the consumption of energy-demanding appliances (e.g., electric vehicles) to off-peak periods.

DR programs can help the users to live in a sustainable and responsible manner. From a technical point of view, to effectively implement these programs, it is necessary to collect consumption information and process them in a way that most of the benefits can be made. In particular, as human environments are ecosystems of heterogeneous digital devices, a holistic view on energy awareness is needed. This requires the development of an energy management system (EMS). To this end, throughout the WP2 (entitled *Definition of the Requirements and System Architecture*) of the MONERGY project it has been decided to develop a HEMS composed of SPs, namely power sensors where electrical appliances are connected, and a SHG where the logic of the system resides. Smart plugs are used to send power consumption information to the SHG through a communication interface. Furthermore, since in WP2 it was shown that existing communication solutions for sensor networks may show coverage problems in home environments, we proposed a solution allowing for integrating wireless devices based on the Zigbee standard, as well as PLC devices based on the G3-PLC standard. Therefore, within WP3 (entitled *User interface and software*) we have designed a network solution to achieve inter-connectivity and interoperability among devices that communicate using different technologies. Besides, we have also designed two GUIs allowing for displaying consumption information through web interfaces. This is necessary to foster awareness and understand user's behaviour.

This deliverable includes the results of the research carried out within WP4 (entitled *Hardware Architecture Analysis and Integration*). The goals of WP4 are: to provide a hardware validation platform that will allow for (a) the validation of the research results of WP3, and (b) carrying out the research activity of WP5 regarding the derivation of energy usage models of inhabitants of Friuli Venezia Giulia and Carinthia regions; to provide the guidelines for the definition of the hardware architecture elements that would enable the most comprehensive set of functionalities for HEMSs and thus to overcome the limits of existing solutions.

The deliverable is organized as follows. Section 2 overviews the state-of-the-art of HEMSs, and discusses some of drawbacks of existing solutions. Section 3 presents the Monergy HEMS. The installation of the Monergy HEMS in the households together with the dataset deriving from the measurement campaign is detailed in Section 4. The experimental HW and SW developments are presented in Section 5. Finally, the deliverable is concluded in Section 5.3.1.

Section 2

Home Energy Management Systems: State-of-the-Art

One of the goals of the MONERGY project is to promote research and innovation in the field of information and communication technologies (ICT), by targeting solutions that have an impact on the reduction of the energy consumption within the households of Friuli Venezia Giulia and Carinthia.

To promote energy saving strategies, it is important to make people aware of their energy consumption. Different studies have been carried out in this direction [Bon12, Bjo10b, Bjo10a, EM10]. In particular, the analysis in [EM10] shows that an increase in energy awareness through feedback mechanisms can lead to considerable energy savings, and in particular, up to the 12% can be obtained by displaying real-time energy consumption information at appliance level (see Fig. 2.1).

HEMSs are the technical systems in which energy consumption and production information can be collected, processed and visualised. Thus, they represent the straightforward means in which sustainability and demand response programmes can be implemented.

The rest of this section is organised as follows: in sub-section 2.1 we first describe different types of HEMSs that have been proposed in the literature. In sub-section 2.2, we present commercial off-the-shelf HEMS and we analyse their technology gaps. The following analysis is carried out to develop the MONERGY HEMS that will be presented in Section 3 and that is being used within the WP5 to derive energy usage models and energy management strategies that are tailored to families in Friuli Venezia Giulia and Carinthia.

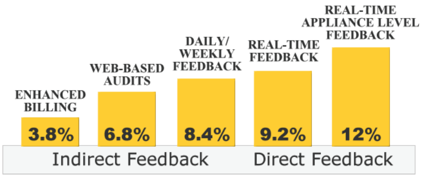

Figure 2.1: Energy saving given by different feedback mechanisms [EM10].

2.1 HEMS

A HEMS is a system of computing components that can be used to manage energy consumption in building environments. Therefore, HEMSs are normally used to collect information of local consumption and production of energy, which are then analyzed and enhanced to improve decision-making of humans and autonomous controllers. In buildings, consumption information can be collected using:

- The smart meter, when accessible. The progressive roll-out of smart meters will provide higher resolution consumption data, which can be used for monitoring and billing purposes by utilities, as well as to be exploited as feedback mechanism by users. Advances in non-intrusive load monitoring (NILM), namely the problem of analyzing changes in the voltage and current flowing into a house to deduct which appliances are used and their individual energy consumption, will provide a means for disaggregating the power profile of loads from the overall household data [Har92, Zei11, Ega13a]. In addition, smart metering allows for the provisioning of energy under adaptive tariff schemes. In DR, a dynamic price signal reflecting the offer of energy in the grid can be used to steer households' energy consumption and keep the overall system balanced.

  Although the previous concepts have not been fully exploited yet, utilities are developing solutions for at least allowing the users to visualize aggregate energy consumption data, even when the smart meter is not installed within the household. An example of a first step toward this direction is given by the Enel Info+ project[1], where the Italian utility ENEL has distributed to a sample of families, a kit composed by a power line communication interface, which reads the data coming from the smart meter, and a small display. Unfortunately, there are not publicly available information

[1] http://www.enel.it/it-IT/reti/smart_info/progetto/

on the refresh time of readings, on the functionalities of this solution, and on the energy saving resulting from the deployment of this feedback mechanism.

- Smart appliances. These are an evolution of the white goods: they are aware of consumed power based on local measurement units or built-in profiles [Elm12]; they can dispatch within the home area network (HAN) information on their energy consumption; they can adapt their power consumption autonomously according to the overall power consumption within the house; they can shift or shed the load [Ene].

  To fully integrate heterogeneous digital devices, built by different manufacturers and based on different technologies, building management systems will have to cope with interoperability issues. The system is required to employ service discovery mechanisms to cope with the mobility and volatility of nodes, which can dynamically join and leave the network community. For instance, electric vehicles are usually charged and disconnected for use, and eventually reconnected for charging. Therefore, smart devices are required to provide a machine-readable description of their properties and functionalities within the network. An extensive discussion of interoperability issues in HEMS is provided by [Mon13a]. Beside interoperability issues, also inter-connectivity issues need to be considered, namely, different communication technologies can be used by different appliances. Therefore, convergence among communication protocols needs to be achieved in order to integrate heterogeneous digital devices. An extensive discussion of inter-connectivity issues is provided by [Lab14], where we have proposed to reach convergence by exploiting the Internet protocol (IP) layer.

  An effort toward the realization of smart appliances and the definition of interoperability mechanisms has been done by the Energy@home association[2]. Different big-players of the household appliances industry together with electricity utilities and telecom operators have defined the interfaces and protocols that can be relevant for systems connected to the electrical grid. The results of the work have been submitted to the working group 21 of the IEC TC-57 who is in charge of developing standards for information exchange for power systems and other related systems including

[2]http://http://www.energy-home.it

Energy Management Systems, supervisory control and data acquisition (SCADA), distribution automation and teleprotection .

- Connecting sensing units to loads to track their consumption. Smart outlets and SPs consist in a network of distributed sensing nodes, which generally provide the possibility to remotely control loads (on/off). This approach is the one adopted by most of currently available HEMSs. It is however worth noting that commercial solutions do not provide local detection of connected loads and any processing of consumption data is done at application level.

From the consideration above, we can summarize by saying that the greatest benefits in terms of energy savings in domestic environments are obtained when real-time information down to the appliance level is displayed. To this end, we have seen that two separate approaches can be followed. The first is to connect each appliance to a smart outlet/plug. The second is to use disaggregation algorithms to identify appliances and derive their energy consumption from the overall metering data. Although disaggregation can replace multiple sensing units, the use of SPs is usually preferred since the technology behind is well known, reliable and cheap. Furthermore, it gives the opportunity to control (switch on/off) individual appliances and it also allows for decomposing the disaggregation problem to smaller groups of devices.

Given the above presented reasons, we have decided to focus on the latter solution. In the rest of this section we describe commercially available HEMSs, while the MONERGY HEMS is introduced in Section 3.

2.2 Off-the-shelf HEMS

Many HEMSs are nowadays present in the market or being developed. These are usually composed by a set of SPs and a device that allows for monitoring power consumption and visualizing data, to which we refer to as smart home gateway (SHG). The SHG can be (a) a computer to which a serial peripherical device with a communication interface is connected (e.g. an USB-Zigbee stick) and in which the management software runs, or (b) an ad-hoc device (e.g., an embedded computer) with a communication interface and a small display to shows energy consumption information. In both cases, the SPs send power readings to the SHG through a communication interface that is in general based on a low bitrate wireless or power line communication technology. We refer the reader to [Lab13], for a detailed review of communication technologies suitable for HEMSs.

Table 2.1 lists some of the HEMSs that are available on the market. As we can see, most of them adopt 2.4 GHz Zigbee communication technology while only one, to the best of our knowledge, adopts PLC technology. In [D'A14], we have derived the communication network constraints for HEMSs. Briefly, we have found that:

- The maximum number of SPs for a HEMS is equal to 19 either in Italy and in Austria.
- The HEMS shall offer a coverage of 100 square meters and up to 4 floors.
- As a consequence of the previous point, the communication channel can be potentially shared among 1500 network nodes, namely SPs, when the communication protocol adopted at the physical layer is wireless. This is a huge amount of network nodes considering the low bit-rate of the communication technologies that are suitable for HEMSs.

Furthermore, we have carried out a test campaign in two apartments using two Zigbee development kits (one working at 868 MHz and the other at 2.4 GHz), and one PLC kit that implements a physical and a medium access control (MAC) layer that are very similar to the ones specified by the G3-PLC standard [Int12]. From the test campaign, we have found that Zigbee at 2.4 GHz may not satisfy the communication coverage requirements, although most off-the-shelf HEMSs adopt it. A better solution would be to adopt Zigbee working at 868 MHz although, also in this case, we have experienced coverage problems. Regarding the PLC solution, we have found that it shows the best coverage over a single floor but it can show coverage problems over multi-floors houses. Another important observation regarding the use of PLC technology is that different logical networks, e.g., HEMSs that are installed in different houses, suffer less from the interference deriving by the channel sharing. This is because different power line networks are physically separated by circuit breakers and power meters.

To mitigate coverage and interference problems, we have envisioned the development of a gateway Zigbee-PLC that allows for integrating both communication technologies in our HEMS. A proof of concept platform will be presented in Section 5.1.

From Table 2.1 we also notice that some off-the-shelf HEMSs are sold with a software development kit (SDK) or an application programming interface (API) while others only offer an application software to manage the system. It is worth noting that none of them offers the possibility

Table 2.1: Commercially available HEMS.

Manufacturer	**Comm. Technology**	**Sampling Resolution**	**SDK/ API**	**Man. GUI**	**Price/SP (€)**
Pikkerton	Zigbee 2.4 GHz	some secs	yes	no	100
Plugwise	Zigbee 2.4 GHz	1 h	no	yes	30
4-noks	Zigbee 2.4 GHz	-	yes	no	40
ThinkEco Modlet	Zigbee 2.4 GHz	-	yes	yes	100
FlexGrid	Zigbee 2.4 GHz	-	no	yes	85
CurrentCost	Wireless Proprietary 433 MHz	1 m	no	yes	18
SLSEnergy	Powerline Proprietary 115-132 kHz	30 s	no	yes	38

to make power readings with resolution equal or lower than the second. This limits the possibility of exploiting these solutions for studying and developing disaggregation algorithms and further to have real-time feedback information. Regarding the Plugwise solution it has to be said that although Plugwise does not provide a SDK, an open source python-plugwise library that decodes the serial protocol employed by the Plugwise USB-Zigbee stick, has been developed and it is freely downloadable from the web [Dam10]. As it will be explained in the next section, this library can be used to make power readings from 9 SPs with interval equal to one second, thus making this solution suitable for the development of disaggregation algorithms.

After an analysis of the cost/benefits[3], we have decided to adopt the kit provided by Plugwise to develop the MONERGY HEMS (see Fig. 2.2). It consists of SPs and a USB-Zigbee stick that allows to communicate with the SPs. The kit will be used together with the open source python-plugwise library to develop the MONERGY HEMS that will be presented in the next section.

[3]Prices showed in Table 2.1 are approximate and obtained through quotations from distributors.

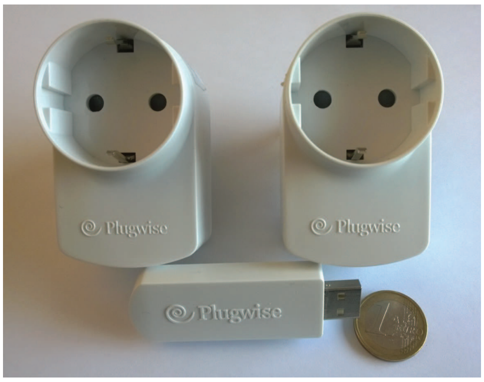

Figure 2.2: Plugwise kit for HEMSs: smart plugs and stick USB-Zigbee.

Section 3

Monergy HEMS

Within the Monergy project, we addressed various aspects of home energy management systems, which generally led to the implementation of prototypes. To carry out the measurement campaign planned in WP5, we made a prototype measurement system based on a combination of open and commercial solutions. The testbed code base is freely available as a Sourceforge project[1]. In this section, we describe the hardware and software aspects of the solution.

3.1 The measurement platform

Our measurement platform is based on the commercial measurement kit Plugwise Basic[2]. The kit consists of a Zigbee network of 9 SPs, each collecting active power measurements from the connected load. The network is interfaced and managed through a USB stick, plugged to an ARM-based mini computer running a Linux distribution. In particular, we employed the RaspberryPi[3] and Beagle Bone[4] boards. Also, to prevent outages on the central gateway we employed the Anker Astro E5 15000mAh external battery[5].

Table 3.1: Specifications of selected boards

Model	Power	CPU	RAM	Connectivity	Price
Raspberry Pi B	700 mA (3.5W)	Broadcom BCM2835 @ 700MHz	512 MB	10/100 Ethernet	35$
BeagleBone Black	210–460 mA (2W)	AM335x 1GHz ARM Cortex-A8	512 MB	10/100 Ethernet	45$

[1] http://sourceforge.net/projects/monergy
[2] http://www.plugwise.com
[3] http://www.raspberrypi.org
[4] http://beagleboard.org/bone
[5] http://www.ianker.com/support-c1-g228.html

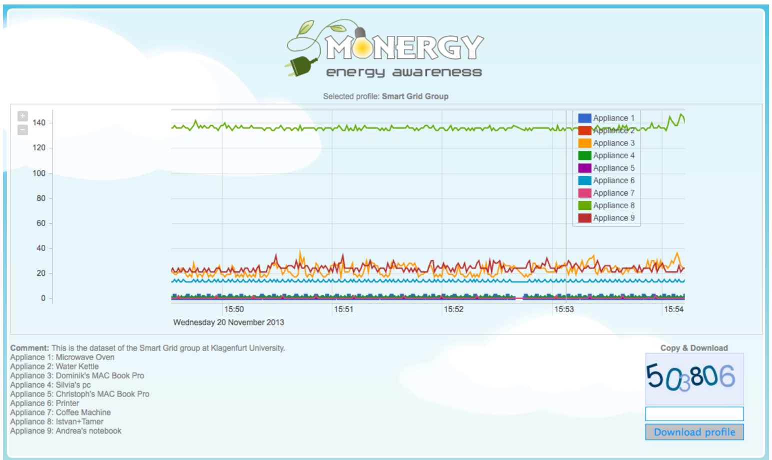

Figure 3.1: The website of the testbed.

3.2 The evaluation testbed

To assess the validity of the chosen solution we deployed the platform in two settings, the Smart Grid lab and the WitiKee laboratory. The gateway was programmed to send data to a database residing on the Monergy servers, as shown in Fig. 3.1. The website provides the capability to scroll power readings over a timeseries chart, which provides a direct understanding of the power profile and it can be used to control the correct collection of data in remote deployments. In this way, we can promptly intervene in case of faults. Also, it allows for downloading the readings as CSV file, which can be more easily analyzed with external tools. While the developed solution constitutes an early prototype of HEMS, it was necessary to add specific expedients to increase the reliability of the solution.

3.3 The daemon

The developed daemon is freely available both as a sourcecode and as a ready-to-use SD image[6]. The software daemon is based on a collector and a manager script (See Fig. 3.2).

The manager starts at bootup and instantiates the collector for the measurements. The manager also updates the collector when a newer version is available, by periodically (default is 5 hours) checking the monergy servers. In this way, it is possible to update all deployments remotely.

[6] http://sourceforge.net/projects/monergy

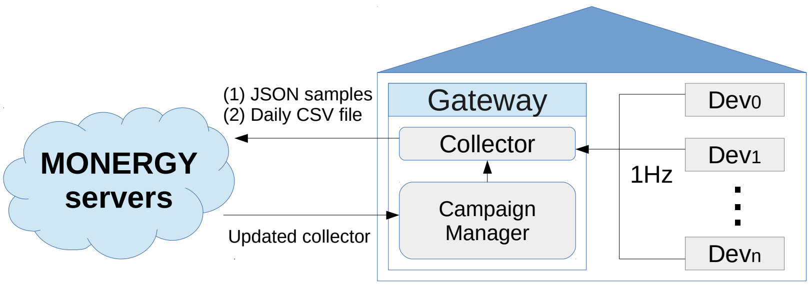

Figure 3.2: The sensing infrastructure.

As for the collector, its control flow takes place in epochs. For each epoch, power measurements are retrieved from each metering node in the network, using the open source *python-plugwise*[7] library. In case of communication failures, such as mispelled packets, the collector skips the node so as to guarantee a uniform epoch duration. At the end of the epoch, if time is enough, the collector tries to retrieve measurements from skipped nodes. Also, to cope temporary node faults and unplugged ones, it keeps a blacklist that prevents it to interrogate them for a specific backoff time.

Storage of collected samples can be: i) local as daily comma separated value (CSV) file, ii) on a remote mysql server with visualization and quick download (Fig. 3.1), iii) a combination of i and ii for double backup, iv) daily CSV files uploaded via sftp to the Monergy servers.

The collector receives as input a configuration file specifying all settings (Code 3.1).

Code 3.1: Collector configuration file

```
{
 "server":"http://www.monergy-project.eu/...",
 "update-en":true,
 "update-server":"http://www.monergy-project.eu/...",
 "update-time":18000,
 "enable":4,
 "apikey":"",
 "local" :"dataset/",
 "sftp-host":"monergy-project.eu",
 "sftp-port":22,
 "sftp-username":"",
 "sftp-password":"",
 "epoch_time": 1.0,
 "blacklist_time":180.0,
 "window_size":900,
 "circles": ["000D6F00035589CF",
            "000D6F0003562BBD",
            "000D6F0003562DF2",
```

[7]https://bitbucket.org/hadara/python-plugwise/wiki/Home

```
            "000D6F0003561F9A",
            "000D6F0003561F91",
            "000D6F0003561751",
            "000D6F0003562C04",
            "000D6F0003562BA6",
            "000D6F0003562BCA"]
}
```

The modality is specified in the field *enable*. The epoch duration is defined through the field *epoch_time*. Also, the backoff time of temporarily unplugged or faulty nodes is defined in *backlist_time*. *window_size* defines the lenght in seconds by which collected samples are moved to the storage. The list *circles* defines the MAC address of all measurement nodes from which measurements should be retrieved. The fields *update-en*, *update-server* and *update-time* set the location and period of updates. The *server* field defines the location of the script handling the mysql storage of data received from the collector (storage modality ii). The *apikey* field is used to authenticate requests to the server, to prevent unauthorized read and write data operations. The *local* field specifies the location to save the daily CSV sample data (storage modality i and iii). The fields *sftp-host*, *sftp-port*, *sftp-username* and *sftp-password* define the SFTP settings for storage modality iv.

Section 4

The Monitoring Campaign and the GREEND Dataset

Publicly available datasets are necessary to assess solutions resulting from research on energy and sustainability. In this section, we describe existing energy consumption datasets and report the measurement campaign undertaken within the monergy project, whose outcome is the GREEND dataset.

4.1 Energy consumption datasets

The effort of providing a complete energy consumption dataset has already engaged the research community. For instance, a widely used dataset in the load disaggregation community is the REDD dataset, which was publically released by MIT in 2011. Many other research institutions followed. Table 4.1 shows existing energy consumption datasets. The electrical features being dealt are the active power (P), reactive power (Q), apparent power (S), energy (E), frequency (f) and phase angle (ϕ).

Table 4.1: Existing datasets for energy consumption in households

Dataset	Location	Duration	#Houses	#Sensors (per house)	Features	Resolution
ACS-F1 [Gis13]	Switzerland	1 hour session (2 sessions)	N/A	100 devices in total (10 types)	I, V, Q, f, Φ	10 secs
AMPds [Mak13]	Greater Vancouver	1 year	1	19	I, V, pf, F, P, Q, S	1 min
BLUED [And12]	Pittsburg, PA	8 days	1	Aggregated	I, V, switch events	12 kHz
GREEND	Austria, Italy	1 year (3-6 months completed)	8	9	P	1 Hz
HES	UK	1 month (255 houses) - 1 year (26 houses)	251	13-51	P	2 min
iAWE [Bat13]	India	73 days	1	33 sensors (10 appliance level)	V, I, f, P, S, E, Φ	1 Hz
IHEPCDS[1]	France	4 years	1	3 circuits	I, V, P, Q	1 min
OCTES[2]	Finland, Iceland, Scotland	4-13 months	33	Aggregated	P, Energy price	7 secs
REDD [Kol11]	Boston, MA	3 - 19 days	6	9-24	Aggregate: V, P; Sub-metered: P	15 kHz (aggr.), 3 sec (sub)
Sample dataset[3]	Austin, TX	7 days	10	12	S	1 min
Smart* [Bar12]	Western Massachussets	3 months	1 Sub-metered +2 (Aggregated + Sub-metered)	25 circuits, 29 appliance monitors	P, S (circuits), P (sub-metered)	1 Hz
Tracebase [Rei12]	Germany	N/A	15	158 devices in total (43 types)	P	1-10 sec
UK-DALE [Kel14a]	UK	499 days	4	5 (house 3) - 53 (house 1)	Aggregated P, Sub P, switch-status	16 kHz (aggr.), 6 sec (sub.)

[1] http://tinyurl.com/IHEPCDS
[2] http://octes.oamk.fi/final/
[3] http://www.pecanstreet.org/projects/consortium/

As observable, GREEND is the first 1 Hz consumption dataset for Austria and Italy. In particular, the selection of consumption scenarios follows the analysis we presented in [Mon13b] and [Lab13]. Our objective is to provide different scenarios, both in terms of residents and devices involved. Also, the campaign is meant to last one year, to observe and model seasonal consumption patterns. As for the electrical features, we decided to collect active power measurements a 1 Hz. This requirement is typical in the load disaggregation community [Zei12] and allows for the identification of more than 8 devices [Arm13].

4.2 Deployments

The first version to be released at the end of October 2014 contains the following scenarios:

- *House #0* a detached house with 2 floors in Spittal an der Drau (AT). The residents are a retired couple, spending most of time at home.
- *House #1* an apartment with 1 floor in Klagenfurt (AT). The residents are a young couple, spending most of daylight time at work during weekdays, mostly being at home in evenings and weekend.
- *House #2* a detached house with 2 floors in Spittal an der Drau (AT). The residents are a mature couple (1 housewife and 1 employed) and an employed adult son (28 years).
- *House #3* a detached house with 2 floors in Klagenfurt (AT). The residents are a mature couple (1 working part-time and 1 full time), living with two young kids.
- *House #4* an apartment with 2 floors in Udine (IT). The residents are a young couple, spending most of daylight time at work during weekdays, although being at home in evenings and weekend.
- *House #5* a detached house with 2 floors in Colloredo di Prato (IT). The residents are a mature couple (1 housewife and 1 employed) and an employed adult son (30 years).
- *House #6* a terraced house with 3 floors in Udine, (IT). The residents are a mature couple (1 working part-time and 1 full time), living with two young children.
- *House #7* a detached house with 2 floors in Basiliano (IT). The residents are an elder couple, one of which is retired.

Table 4.2: Device configurations in the monitored households

House	Devices
0	Coffee machine, washing machine, radio, water kettle, fridge w/ freezer, dishwasher, kitchen lamp, TV, vacuum cleaner
1	Fridge, dishwasher, microwave, water kettle, washing machine, radio w/ amplifier, dryier, kitchenware (mixer and fruit juicer), bedside light
2	TV, NAS, washing machine, drier, dishwasher, notebook, kitchenware, coffee machine, bread machine
3	Entrance outlet, Dishwasher, water kettle, fridge w/o freezer, washing machine, hairdrier, computer, coffee machine, TV
4	Total outlets, total lights, kitchen TV, living room TV, fridge w/ freezer, electric oven, computer w/ scanner and printer, washing machine, hood
5	Plasma TV, lamp, toaster, stove, iron, computer w/ scanner and printer, LCD TV, washing machine, fridge w/ freezer
6	Total ground and first floor (including lights and outlets, with whitegoods, air conditioner and TV), total garden and shelter, total third floor.
7	TV w/ decoder, electric oven, dishwasher, hood, fridge w/ freezer, kitchen TV, ADSL modem, freezer, laptop w/ scanner and printer

The device configurations for the selected households are shown in Table 4.2. Eventually, we notice thaa another household has been monitored for various months in Carinthia. The household is a detached house with 2 floors in Villach, whose residents are three university students with irregular working days. Due to an initial faulty hardware we observed missing data for several days, which led us not to include the data already in the first release. We will provide the outcome of such deployment in the second release, along with further installations we are currently conducting.

4.3 The NILM toolkit

The NILM toolkit[1] is an open source toolkit for non-intrusive load monitoring [Bat14]. The framework, written in Python, allows for importing various of the datasets reported in Table 4.1 to perform data analysis. The aim is to provide a platform for researchers using those datasets, for which a data cleaning and preprocessing tool can be of great value. The straightforward use case is load disaggregation for which the framework aims at providing benchmarking capabilities. The framework provides state-of-the art approaches, such as based on hidden-markov models, as well as defines metrics to assess different implementations.

To provide full interoperability, the nilmtk developers also proposed a set of metadata by which energy datasets can be modeled [Kel14b]. The nilm metadata[2] captures both building characteristics, such as floors and rooms, as well as electrical appliances, for which basic categories are provided out of the box. The metadata are specified as YAML format[3] text files, which are stored alongside the dataset data. For the GREEND dataset, we modeled the scenarios described in Sect. 4.2 and wrote a script importing the metadata and the dataset data into the high-performance hierarchical data format (HDF5) that can be handled by the nilm toolkit.

[1] http://nilmtk.github.io
[2] https://media.readthedocs.org/pdf/nilm-metadata/latest/nilm-metadata.pdf
[3] http://www.yaml.org

Section 5

Experimental Hardware and Software

As explained in the previous sections, commercial HEMSs suffer strong limitations that reduce their broad deployment. The topic was deeply addressed in WP2 and well documented in the first deliverable of the project [Lab13]. The research therein performed was carried out considering the characteristics of commercial devices, the needs of the consumers, and the characteristics of the residential buildings, where such devices are supposed to be deployed. The latter aspects were highlighted by the survey that was performed in Friuli-Venezia Giulia and Carinthia. Basically, the study showed that the main limits of commercial HEMSs are connected to three main areas. From the bottom level (technology aspects) up to the top level (user interface), they are the following.

Coverage. Commercial HEMS do not provide adequate coverage due to the limits of the communication technology deployed to query and control the smart plugs. Most of the commercial HEMS rely on wireless transmissions. The widespread wireless standard is Zigbee operating at 2.4 GHz. Zigbee at 2.4 GHz is not able to ensure reliable inter-floor, i.e., between floors, and intra-floor, i.e., within the same floor, communications in residential buildings of Friuli-Venezia Giulia and Carinthia. We refer to Section 2.2 for further details.

Installation. From the survey analysis, it turned out that the maximum number of household appliances in Friuli-Venezia Giulia and Carinthia is 19. In ideal terms, each device should be equipped with a SP that allows for the remote control (switch on/off) and the power monitor. Commercial HEMSs tend to such ideal case providing a large set of SPs controlled by a central unit. Indeed, users are not prone to a pervasive HEMS architecture because the installation of the SP is sometimes uncomfortable. For instance, let us imagine the installation behind the fridge or the washing machine. Furthermore, such devices consume energy by themselves. The higher the number of SPs, the higher the power consumption. Finally, we note that when we increase the number of communicating nodes we experience larger coexistence problems.

Usability. HEMSs provide a multitude of ways to control and monitor the devices. The information can be accessed via PC, tablet or smartphone, the HEMS can be queried outside the house, and the data can be even uploaded to the cloud. However, in most of cases, the graphical user interface (GUI) is counterintuitive, complex and far from being usable. The HEMS software provides a wide range of statistics about the consumption, but at the end, the final goal is lost because the actual consumption is rarely showed in a clear and direct fashion, on a dedicated device that does not need any particular skill to be deployed, such that all users can get benefit from their HEMS to better manage their energy.

This section presents practical solutions, both software and hardware, to overcome the main limitations of current HEMSs. The work is based on the research activity performed within WP4 and partly in WP3, aimed to provide the hardware architecture and communication technologies that enable the most comprehensive set of functionalities for the HEMS. The main outcomes are three, one for each of the three areas where current EMS are weak.

Section 5.1 presents the first, a hybrid wireless-wireline architecture that allows achieving the requirements in terms of coverage that were pointed out by the survey. Wireless still exploits Zigbee at 2.4 GHz, enabling backward compatibility with current commercial systems, since Zigbee represents a standard in the field of home energy monitoring. Wireline is implemented with power line communication (PLC) technology. PLC is attractive because it exploits the power delivery infrastructure to convey information content. No new wires are required and the installation effort of PLC is as much limited as that required by the installation of wireless devices.

We believe the turnkey element to setup an efficient hybrid wireless-wireline network is the communication protocol. The dominant approach to manage heterogeneous communications is based on general purpose middleware solutions that provide a wide range of features at the price of high complexity. Indeed, we develop a simple communication protocol with low overhead that enables fast communications of low amounts of data minimizing the channel occupation to limit the coexistence problems. We demonstrate that convergence is possible at low levels of the ISO/OSI stack, though we do not exclude that more sophisticated approaches are possible to provide convergence exploiting the IP protocol.

Section 5.2 presents the second outcome of the research activity of WP4, the aggregate power consumption monitoring device. The device is aimed to address the setup limitations of current HEMS systems providing a centralized monitoring solution that substitute the pervasive installation of smart plugs throughout the residential building. The device can be combined with the load disaggregation algorithms discussed in [Ega13b, **?**], to extract the information about the power consumed by each household appliance from the measure of the aggregate power consumption on top of the power delivery network, i.e., close to the energy meter. The device has been designed, realized, tested and validated on the field. Differently to commercial systems, the device is full-custom, runs several power readings per second, for accurate power estimation, and it is designed for a secure and easy installation in the main electrical panel of residential buildings. Furthermore, it can be fully programmed to implement new features.

Section 5.3 discloses the third important outcome on HEMS improvements, a GUI designed to ease the power monitoring task. The GUI exploits the information extracted from the survey on the willingness expressed by the users about the user interface. Namely, it is a dedicated device that delivers power monitoring information in the simplest way possible. We have selected a hardware platform that fits the requirements suggested by users and we have developed a GUI that runs on it. The system can operate with both the current commercial systems, as that deployed by the measurement campaign, and the aggregate power meter described in Section 5.2.

5.1 Wireless to Wireline Gateway

Coverage limitations make frustrating the energy monitoring experience with current commercial systems. Communication technologies suffer strong limitations, as we pointed out in [Lab13], but users do not perceive such limits and they take for granted that HEMS reach every corner of the house at the same time, from the fridge in the cellar to the boiler in the attic.

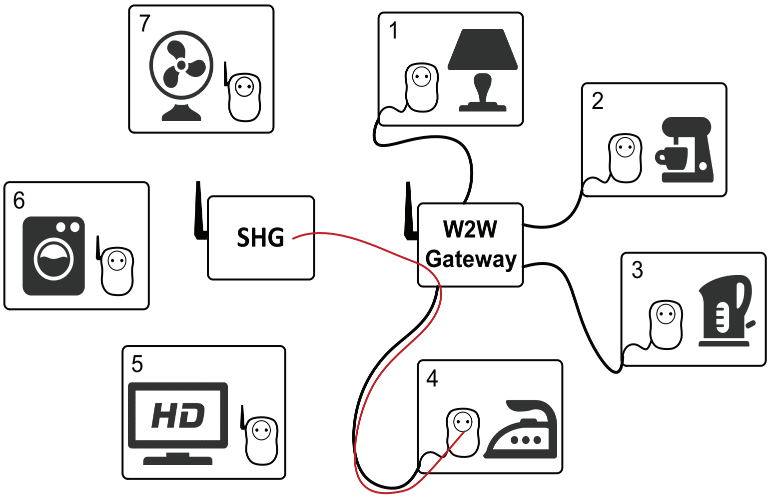

Figure 5.1: Block diagram of a hybrid EMS network. The communication path toward smart plug #4 is also shown.

We believe that networking limits can be overcome combining wireless and wireline, and we propose a hybrid communication network that fullfills the communication requirements pointed out by the survey. The solution leverages on a multi-technology gateway, namely a wireless to wireline (W2W) gateway.

Conventional HEMS networks are as depicted in Fig. 5.1. They consist of a SHG and several SPs. The communication between the SHG and the SPs must be bidirectional. In detail, the SHG a) queries the SP to get the power consumption, b) gets back the information and, possibly, c) forwards the command to switch on/off. The SHG controls the whole network thus playing a central role and we can model the network as star-shaped. The SHG is the center of the star network, the SPs are the network terminations. Now, as shown in Fig. 5.1, SPs can belong to heterogeneous branches of the network. When this is the case, the W2W gateway translates data traffic from one communication network to another. In this respect, the gateway extends the communication capabilities letting the SHG able to communicate with devices that are equipped with different network interfaces. The strength of the gateway is that it appears transparent to both the SHG and the plugs. For instance, in Fig. 5.1 the W2W links the (wired) SP 4 to the SHG.

The choice of the wireless and wireline standards is arbitrary. We propose the use of Zigbee and G3-PLC. The choice of Zigbee is based on backward compatibility reasons. Most of the commercial devices adopt Zigbee at 2.4 GHz because the standard enables very low power consumption, advanced mesh network functionalities and an adequate transmission speed for most of the HEMS needs. Indeed, the choice of the wireline technology is less trivial. The use of PLCs for metering purposes have been explored for quite a long time and several PLC standards have been already proposed, as Konnex, X10 and UPB. Metering via PLC has been the interest of distribution system operators (DSO) mainly. DSO aim to control the electronic meter installed in the customer premises by communicating via their own infrastructure. The goal is to be independent from third-party telecommunication networks. The widespread field deployment of metering via PLC has been setup in Italy, where more than 40 million meters communicate with the central control stations managed by the DSO. Initially, PLC standards were designed for very low speed applications. Recently, the evolution of the power delivery network toward the smart grid has introduced the need of advanced communication capabilities and higher data rates. Such technology improvements fit the needs of HEMS as well.

PLC is divided in two classes, broadband and narrow band. Broadband PLC is intended for high-speed multimedia streaming applications and it is a valuable alternative to WiFi. Broadband PLC occupies the large frequency band between, say, 2 MHz and 100 MHz and it can achieve up to 500 Mbps at the physical layer. Indeed, narrow band PLC has been designed for command&control, home automation and remote metering applications, it enables communications up to 500 kbps and it occupies the low band portion, below 500 kHz. Strictly, the range of frequencies is defined by standardization bodies. For instance, in Europe, the frequency bands where PLC are required to operate are determined by European Committee for Electrotechnical Standardization (CENELEC) and they are four, A (3 - 95 kHz), B (95 - 125 kHz), C (125 - 140 kHz) and D (140 - 148.5 kHz). Among narrow band PLC, the most important standards are PRIME, G3, IEEE P1901.2 and ITU-T G.hnem, and we refer to [Lab13] for a brief review of their main characteristics. The most widespread are only PRIME and G3. Furthermore, IEEE P1901.2 simply ratifies the possible use of modulation schemes similar to PRIME and G3, adding some further coexistence mechanisms. Based on our field experience, we found G3 platforms available to us to perform better than PRIME platforms. Based on this, G3 was selected as a good system platform for the realization of the HEMS. G3 has been designed in two variants. For the scope of the proof-of-concept, we choose G3-PLC. G3-PLC is intended for Europe and it can operate in any of the CENELEC bands or a combination of them. G3-FCC is intended for the US and it operates in the FCC band.

The following sections detail the proof-of-concept wireless to wireline gateway that we have realized. Section 5.1.1 is focused on hardware aspects. Section 5.1.2 provides some more details about the protocol that we have implemented to enable the communications on the hybrid HEMS network. Some remarks on the possible improvements starting from the proof-of-concept are reported in Section 5.1.3.

5.1.1 Proof-of-Concept Hardware Details

The aim of the proof-of-concept is to demonstrate the feasibility of a hybrid network infrastructure where both wireless and wireline communication technologies are deployed to solve the limits of current HEMSs in terms of coverage. The simplest possible proof-of-concept consists of three elements, a SP, the gateway and the SHG, i.e., the branch toward SP 4 of the complex network in Fig. 5.1. All other branches of the network in Fig. 5.1 are not important to validate the feasibility of the hybrid network.

For the purposes of this proof-of-concept we equipped the central unit with a PLC interface. The example is motivated by the practice. In fact, we note that the SHG must be constantly kept on to enable the user getting information about the power consumption whenever desired. Now, to avoid limits of battery-fed systems, we imagine the SHG to be fed by the power delivery network. Thus, we can exploit the wired connection to signal via PLC. The SP is wireless. However, we do not exclude an alternative configuration where the SHG is wireless and the SP is wired.

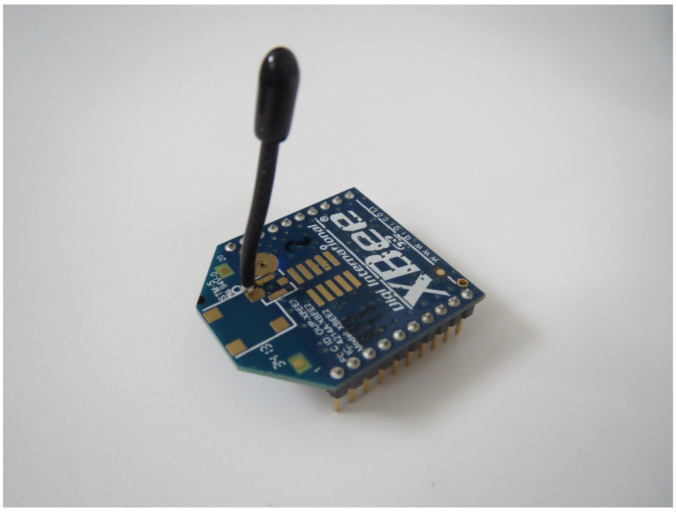

Figure 5.2: Zigbee transceiver by Digi.

Now, let us present the technical details of three elements that make the proof-of-concept. Firstly, let us focus on the smart plug. The smart plug is well documented in Section 5.2, as it has been fully developed and made for the purposes of the project. It embeds a wireless interface that is compliant with Zigbee at 2.4 GHz. The transceiver is supplied by Digi and it is similar to that embedded in the Plugwise modules. We decided to equip the module with a Zigbee interface to be consistent with most of the existent HEMS. The interface is capable of up to 250 kbps. Fig. 5.2, shows the transceiver module that is mounted in the smart plug.

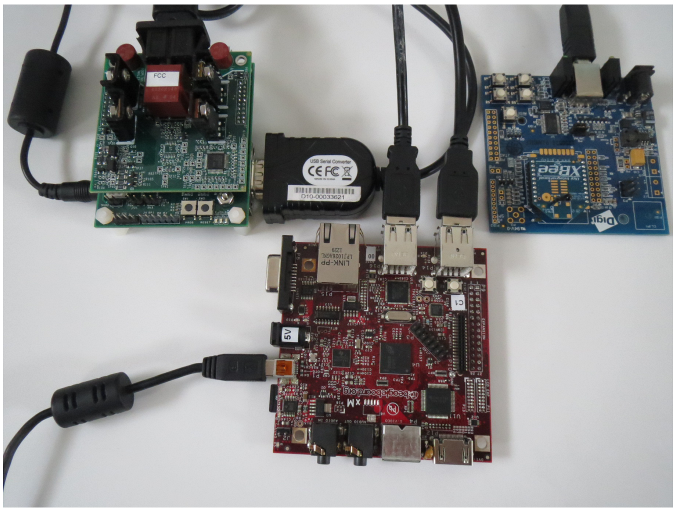

Figure 5.3: W2W gateway. The embedded PC, the wireless module and the PLC module are the red, blue and green board, respectively.

The gateway is an embedded PC with two network interfaces. The interfaces are compliant with Zigbee at 2.4 GHz and G3-PLC. We implement the gateway on a well-known platform, the Beagleboard xM. The Beagleboard xM[1] is equipped, moreover, with an ARM Cortex A8 at 1 GHz, dedicated hardware for video processing, a fixed point digital signal processor, 4 USB ports and an Ethernet port. The computation capability of the platform is exceeding the actual needs, and the gateway can be downsized on a cheaper though less performing platform. In this respect, we do not exclude the use of a microcontroller instead of the ARM Cortex A8 microprocessor. In fact, the unit simply controls and forward messages between the interfaces at low rate. Network capabilities are provided by separated transceivers that are connected via USB to the embedded PC. Fig. 5.3 shows the embedded PC platform,

[1] http://beagleboard.org/beagleboard-xm

the wireless module, and the wireline module. The wireless interface is the same installed in the smart plug. The wireline interface is a G3-PLC modem supplied by Maxim. We let the G3-PLC modem signaling in the resultant bandwidth obtained merging CENELEC bands B and C. We avoid CENELEC A since this band is intended for communications by DSO and, further, because we have experienced the largest levels of noise (worst performance). According to the configuration that we adopted, the maximum data rate is about 16 kbps. The communication from the embedded PC toward the network modules is serial, via standard serial-to-USB interfaces, as FTDI adapters. The embedded PC runs an embedded Linux distribution, Angstrom. A C-written program controls the serial ports, forward messages, check acknowledgments, and performs all other tasks according to the algorithm specified in Section 5.1.2.

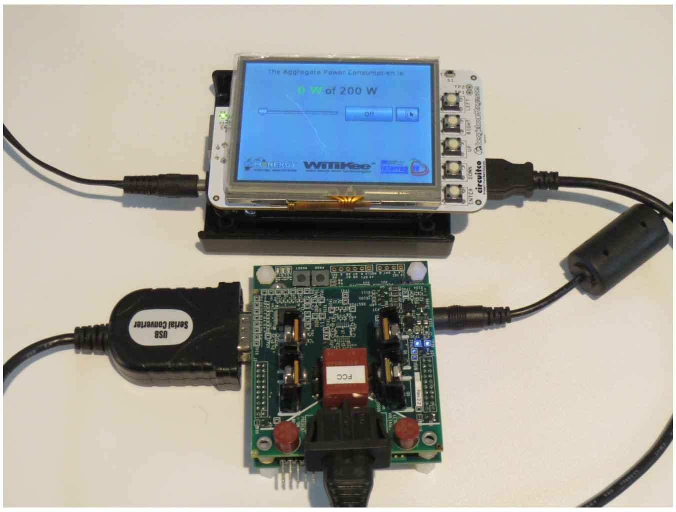

Figure 5.4: The embedded PC and the PLC interface of the SHG on top and bottom, respectively.

The SHG is the central node of the HEMS. We implemented the SHG functionalities on an embedded PC as well. Fig. 5.4 shows the implementation that we have setup for the proof-of-concept. Basically, we implement the central unit on a Beaglebone Black. The Beaglebone Black is an extremely performing and cheap platform and it is equipped, moreover, with an ARM Cortex A8 at 1 GHz, 4 GB of MMC memory, 1 USB port, 1 Ethernet port and a SD-Card reader. On the embedded PC we install a TFT LCD display and we connect the G3-PLC module to the USB port via a standard serial to USB cable. The embedded PC runs Linux. The user interface, displayed on the monitor is the first release described in Section 5.3 and it provides standard functionalities to monitor the power consumption and to switch on/off the remote module. It further allows setting a power threshold. When the actual power consumption exceeds the threshold, the SHG alerts the user with a change of the graphical interface and the SP starts buzzing. The user interface is written in Java. The communication port is controlled in a C-written program that is interfaced to the Java application via Java native interface.

Network interfaces implement the ISO/OSI stack up to level 2. This is valid both for Zigbee modules and PLC modules. It follows that the data exchanged via the serial port is always the payload at level 2. The proof-of-concept fulfills the suggestions in [Ber13] that invoke convergence at level 3. In fact, by adding a communication protocol as payload of level 2 we are basically implementing a custom level 3 of the ISO/OSI stack.

5.1.2 Protocol Insights

We herein describe the communication protocol that we developed and implemented to demonstrate the feasibility of an heterogeneous network.

The proof-of-concept network is made by a SHG and a SP that are interconnected via a W2W gateway. The communications between the SP and the SHG is bidirectional and controlled by the SHG. The SP simply replies to SHG requests. For instance, providing the power measure or reporting the status (on or off). We account for the central role of the SHG, and we develop an unbalanced communication protocol that favors the propagation of the messages from the SHG to the SP and waits for the reply in the opposite direction. The protocol defines the structure of the data packets and the algorithm implemented by the gateway to manage the traffic from both the wired and wireless interfaces.

Firstly, let us focus on the data packets. Fig. 5.5 discloses the structure of the packet. Basically, the data packet consists of 8 bytes and 6 fields. The field dimension is fixed, but the field content depends on the recipient of the data packet. We denote with CMD and ANS the data packets from the SHG to the SP and from the SP to the SHG, respectively. The fields INI, CNT, IDN and EMP are common. INI is the initializer field, it delimits the beginning of a new packet and it is intended for synchronization. Basically, it lets the receiver be aware about a new upcoming packet. INI is a constant field of 1 byte and we let it be equal to the character '$*$'. CNT is a counter field of 1 byte as well. The CNT number identifies the packet and it enables a) keeping trace about requests, b) replying only once to each request, c) repeating the request in case

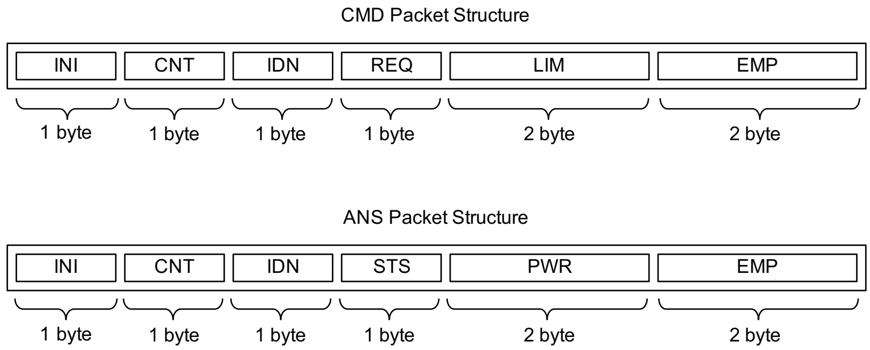

Figure 5.5: Structure of a CMD and ANS data packet on top and bottom, respectively.

any reply has been received. Basically, with CNT we can implement an acknowledgment mechanism similar to that adopted by TCP, though simplified. IDN is a basic receiver address of 1 byte. IDN allows addressing up to 128 devices. The number is adequate as far above 19, i.e., the number of plugs needed by users of Friuli-Venezia Giulia and Carinthia according to the survey. Finally, EMP is an empty field of dimension 2 bytes that is intended for future developments. Between IDN and EMP, packets consist of two additional fields. One of size 1 byte, one of size 2 byte. In CMD, they are referred to as REQ and LIM, respectively. In ANS, they are referred to as STS and PWR, respectively. REQ defines the SP status requested by the SHG. It can be the character 'Y', to indicate that the SP must be switched on, or the character 'N' to indicate that the SP must be switched off. The SP changes (or keeps) its status according to REQ. With 8 bits, i.e., the actual size of REQ, we apply a simple channel coding that improves robustness. In fact, REQ could be as small as 1 bit because the number of states is 2. LIM contains the information about the power limit constraint defined by the user. When the power consumption exceeds LIM, the SP starts buzzing. STS contains the current status of SP. Note that STS is a field of the ANS packet, and thus it is directed to the SHG. Basically, STS acknowledges the status requested by the field REQ of the prior CMD packet. Finally, PWR provides the information about the power consumption measured by the SP.

Now, let us focus on the protocol. It endorses the need to reach convergence at layer 3 of the stack ISO/OSI. Several papers deal with the convergence at layer 3 [Lab14], [Ber13]. They all suggest the use of the IP protocol since IP is the most widespread. For the purposes of the proof-of-concept, a simplified protocol that simply validates the

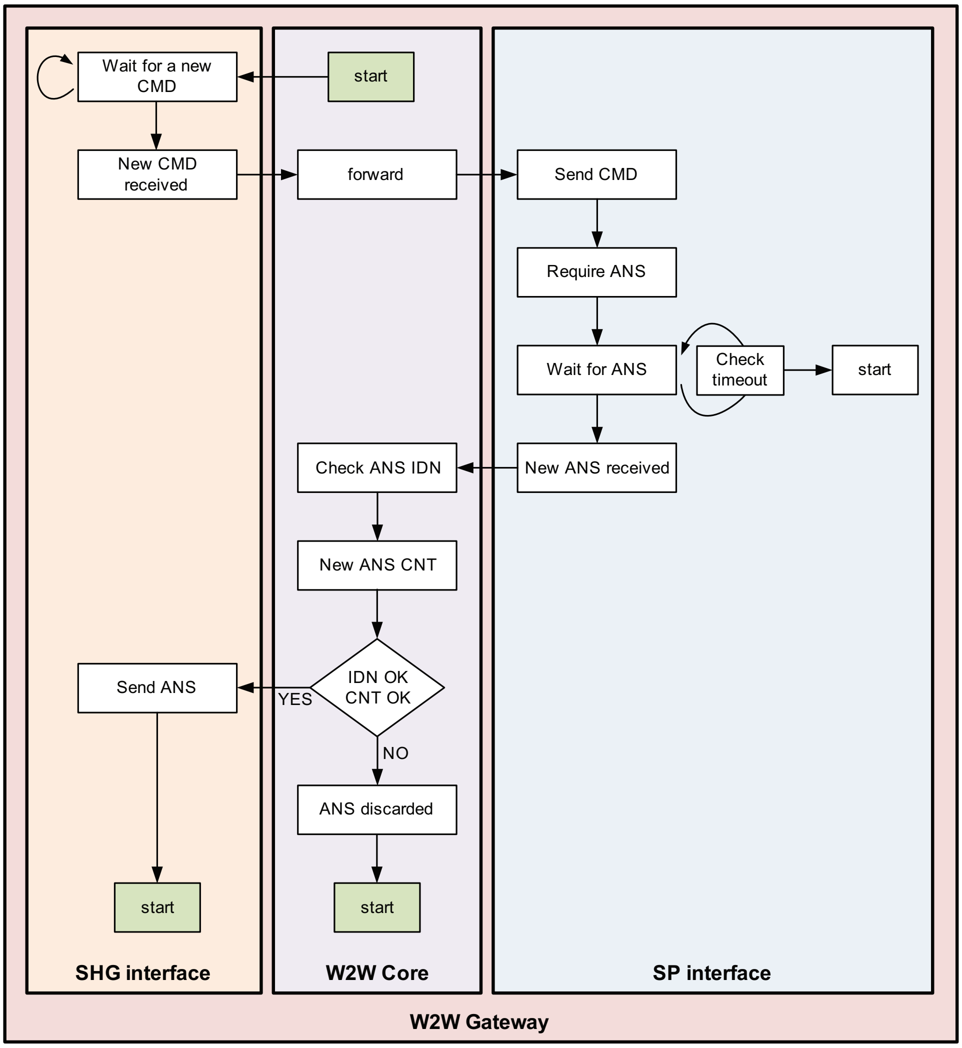

Figure 5.6: Communication protocol implemented in the W2W gateway

convergence at layer 3 is sufficient. Fig. 5.6 is a block diagram of the protocol as implemented in the proof-of-concept demonstrator. Most of the steps are performed by the W2W gateway, that is responsible for the management of the traffic on both the wired and wireless interface. The left side of the Figure depicts the interface toward the SHG. The right side represents the interface toward the SP. The protocol consists of the following steps.

- *Wait a new packet from the SHG.* This is the starting point and it reflects the importance of the SHG. With no CMD packet from the SHG, no communication is setup between the interfaces. The gateway is supposed to stop at this step until a new packet comes, as represented by the circle arrow.

- *Receive and forward a new CMD packet.* The CMD packet is sent toward the SP. In this case, no control is applied. However, we do not exclude to implement a control on the receipt address (IDN) of the packet to avoid forwarding packets when the receiver is not on the SP network.
- *Request an answer.* The gateway requests an answer from the SP and it waits, as represented by the circle arrow, until timeout. If timeout is achieved, the request is get lost and the algorithm starts again and the gateway waits for a new CMD packet.
- *Check IDN and CNT.* When a ANS is received, the gateway checks whether the IDN is correct and the CNT is consistent with that of the prior CMD packet. If controls fail, the packet is discarded and the algorithm starts again.
- *Forward the ANS packet.* If controls pass, the packet is sent to the SHG network interface.

Note that the reception of a new packet implies a first check on the packet integrity, i.e., all fields have been received, and a second check on a valid INI field. Any data that do not pass these tests is considered garbage, it is disregarded, and the gateway still waits for a new upcoming packet.

The protocol must take into account delays due to transmission latency and the timeout interval must be calibrated according to the underlying technology and the characteristics of the network traffic. We get these values from experimental trials.

5.1.3 Protocol Improvement Remarks

The proof-of-concept prototype validates the use of multiple communication technologies to overcome coverage limitations of current HEMSs. It further demonstrates that the convergence at layer 3 is feasible, even with a simple custom protocol that we have developed and described. Clearly, the protocol can be extended to include multiple-node networking aspects. In its current version, for instance, it does not account for a new node join, or it does not implement any type of acknowledgment. However, all these aspects can be addressed without affecting the validation role of the proof-of-concept.

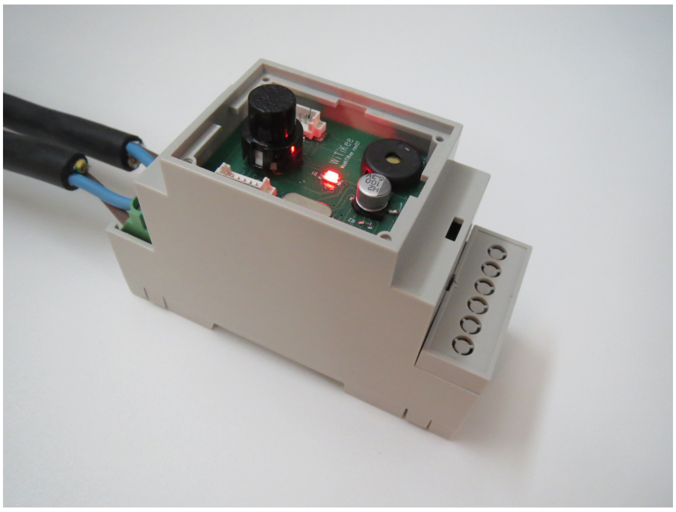

Figure 5.7: The aggregate power meter.

5.2 Sub-Meter for Aggregate Power Monitoring

HEMS platforms consist of a SHG and several smart plugs. The smart plugs must be installed close to the device they are supposed to monitor. Pros are the following.

- *Remote control of the device*. The user can switch it on/off from the user interface of the HEMS.

- *Accurate power monitoring*. The SP provides the accurate information about the power consumption of the device where it is installed on.

However, the system is affected by the following cons.

- *Large installation effort*. In some cases, the installation of the SP close to the device is not a trivial task and yields to a frustrating experience with HEMS systems. For instance, let us consider the installation behind a fridge built-in the kitchen.

- *Coverage limitations*. As discussed in Section 5.1, the HEMS may not be able to cover the entire area of the premise. It follows that devices distant by the SHG may be unreachable.

Definitely, the resultant structure is pervasive. Now, to overcome the main limitations of current HEMS, we follow a complementary approach that deploys only one SP installed on top of the power delivery network and that enables monitoring the power consumption of the household appliances from a single, aggregate power measure.

We have designed and developed a custom sub-meter that enables monitoring the aggregate energy consumption. Basically, the device performs as the electronic meter deployed in Italy by the DSO for billing purposes, but it lets the information about the consumption be available for further processing and display purposes. We refer to the device as aggregate power meter (APM). The power consumption of each device can be obtained processing the aggregate power consumption measured by the APM with the load disaggregation algorithms discussed, for instance, in [Ega13b]. The use of a single device is beneficial for a multitude of reasons. For instance, it yields to a less pervasive installation because only one SP must be installed, namely, the APM, the cost can be limited because the number of nodes of the HEMS network is low, and the problem of interference can be mitigated because the number of SPs that share the wireless medium for communications is strongly reduced. The main drawback is that the device does not allow for the complete control of the appliances, i.e., switching them on/off. Fig. 5.7 is a picture of the device.

Figure 5.8: Installation of the Plugwise module in site #4. The red box highlights the modules.

The enclosure enables mounting the APM on the DIN rail of the main panel. It occupies two standard DIN modules, the same space of typical circuit breakers. The aim is to let the installation of the APM be as simple and safe as possible, to overcome the strong limitations that we experienced during the field trial with Plugwise modules. Fig. 5.8, shows the installation of the Plugwise module to monitor the overall power consumption. It refers to the SP that we deployed in House #4 to monitor the lights and outlets circuits. Plugwise packaging does not allow for a safe and easy installation even though the modules supply the currents of the main panel, i.e., 16 A. In particular, modules are not suited for DIN rail mounting and wire terminals are small and not appropriate for large-section wires. Beside safe packaging, we deployed wire terminals of large dimension, for wires of size up to 10 AWG / 5.26 mm^2 and we design the circuitry to deliver currents up to 20 A. Fig. 5.9 is a real installation of the APM module in House #5 of the field trial.

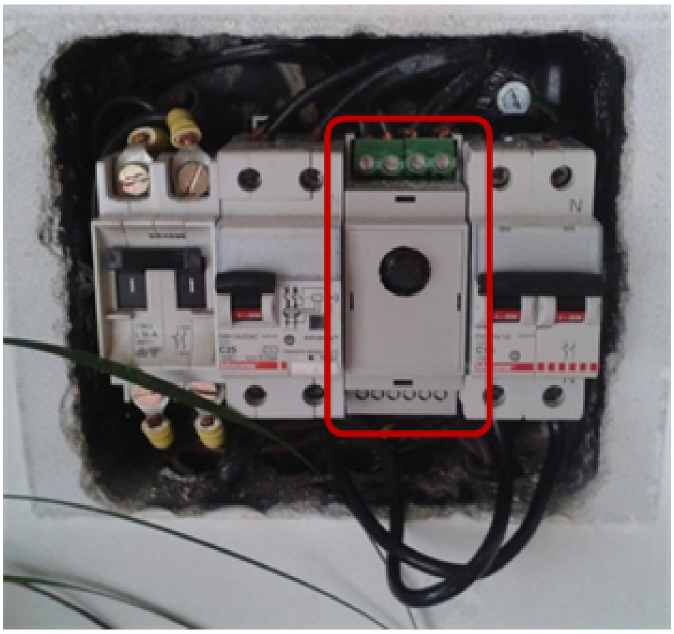

Figure 5.9: Installation of the APM in site #5. The red box highlights the device.

The APM measures the voltage, the current and the real (active) power consumption. The current measure is performed by a Hall-effect sensor. The power measure is obtained combining the current and voltage measure. All the measured values are available, can be exported and collected by the SHG, if required. The APM unit is equipped with a micro controller unit (MCU) and a transceiver module. The micro controller is a cost-effective MCU of the Atmega family, provided by Atmel. The transceiver is a Digi Xbee module, a Zigbee compliant unit that operates at 2.4 GHz. The transceiver is the same deployed in the W2W gateway. Fig. 5.10 shows the PCB boards that make up the APM.

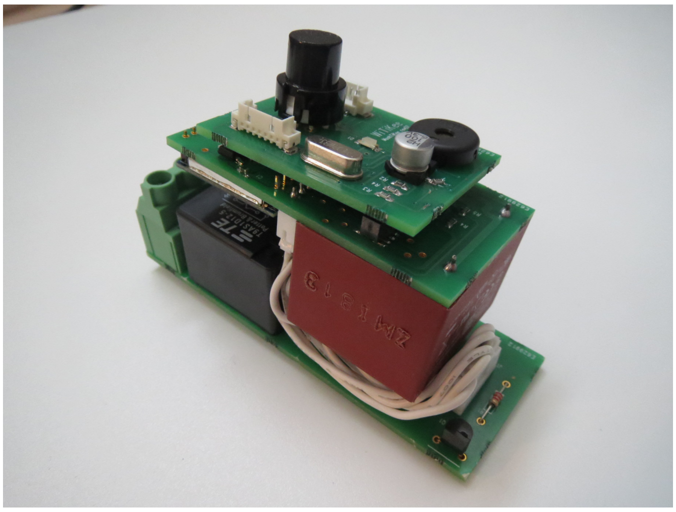

Figure 5.10: Printed circuit boards that make up the aggregate power meter module.

The APM is fully programmable with the standard integrated development environment (IDE) tool of Arduino[2]. The programming language is similar to standard C. The IDE interface is based on the Wiring project[3]. The software design embraces the open-source view and it allows the user to implement custom functionalities with simple software/hardware tools. The code can be uploaded to the MCU using a standard Arduino board, as Arduino Uno, as in-system programmer (ISR). On the top APM board, we soldered a standard connector that enables the communication with the ISR.

The APM performs power measures with sampling period lower than one second. This result puts the APM beyond current state-of-the-art EMS platforms, that provide measures with a resolution never below one second. The high sampling frequency may enable accurate load disaggregation and, ultimately, the exact power consumption estimate for each household appliance.

5.3 GUI for Small Displays

In WP2, we conducted a small survey study on our project website. We addressed aspects such as the characteristics of households, type of electrical appliances used and occupant behavior. The survey was targeted to people older than 18 living in Friuli Venezia Giulia and in

[2]http://www.arduino.cc/
[3]http://wiring.org.co/

Carinthia, it required about 15 minutes to be completed and it consisted of 43 questions grouped in 5 different sections:

1. Household information.
2. Use of electric devices.
3. Sensitivity towards energy consumption and renewable energy generation.
4. Sensitivity and expectations towards technology.
5. Demographic information.

We collected 340 full responses out of 397 participants. The survey was meant to have a first idea on the analogies and differences in energy usage of people living in the two regions, and further to derive the communication network requirements for the HEMS. A deep analysis of the survey results can be found in [Lab13, Mon13b, D'A14].

Within the survey, and in particular, within the section "Sensitivity and expectations towards technology," we have asked the following questions:

- Do you think that a system capable of showing the energy consumption of electric devices and the corresponding costs could be useful to lower your electric bills?
- How would you like to accede to those information?

The first question received the 80% and the 74% of positive answers respectively from the Italian and the Austrian participants. Furthermore, about the 50% of Italian participants stated that they would like to receive the info regarding energy consumption using an ad-hoc touch screen display installed at home, while the remaining 50% through their computer or smart-phone. In Austria, the situation is different, only about 27% of participants would like to visualize the information on an ad-hoc touch screen display installed at home. In order to satisfy both needs, within WP3, which is the WP dedicated to the development of users' interfaces, we have developed both a GUI that runs on a web server, and thus that is accessible using either a computer or a smart phone, and a GUI that can be visualized on a small touch screen display that can be mounted on the Monergy SHG (see Section 3). The former was described in [Lab14], while in the rest of this section, we briefly describe the developed GUI suitable for a small display, e.g., the one shown in Fig. 5.4.

It is worth noting that the use of an ad-hoc display that can be directly connected to the Monergy SHG shows some advantages w.r.t. the use of a computer or a smart-phone, i.e., it does not rely on Internet/intranet connectivity and it does not imply the user to own a computer or a smart phone. Furthermore, its cost is given by the additional touch screen display, e.g., a 4.3 inches touch screen LCD for a beaglebone black costs about 40 euros. Clearly, the adoption of one solution does not exclude the other, namely, the developed GUIs can work contemporary.

5.3.1 The GUI for Small Displays

We herein describe the GUI that we have developed for being visualized on a small touch screen display of 3.5 inches that is directly connected to the Monergy SHG (see Fig 5.4). Basically, we have developed two GUI releases. The former is designed to be simple. The goal is to let the EMS experience be easy to all users. The set of functionalities is limited, but sufficient for the most elementary tasks. The second GUI brings the most advanced EMS functionalities to the embedded device, with the touch screen display. Both have been developed in Java, using the Swing library [Ora14].

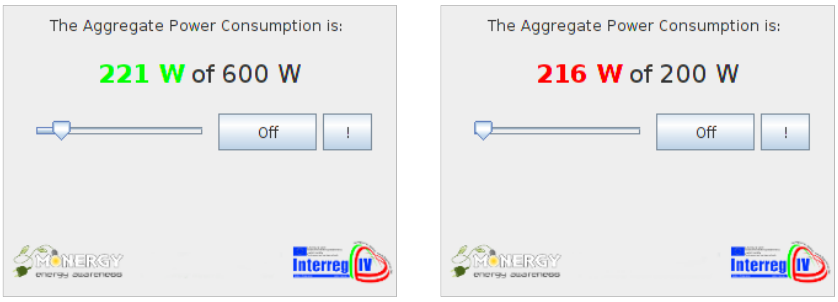

Figure 5.11: Two screenshots of the release one of the GUI. On the left, when the consumption is lower than the threshold. On the right, the opposite case.

Let us focus on the first release, R1. Fig. 5.11 are two pictures of the GUI. The interface is simple, it reports the power consumption and it is equipped with a scroll bar and two buttons. The buttons enable switching on/off the remote SP and resetting the local network interface. The power consumption is reported in W or kW, depending on the actual value. Beside the power consumption, a power limit value is also shown. The power limit is a simple power threshold value. When the actual power consumption is lower than the threshold, the power consumption is depicted in green, otherwise in red. Fig. 5.11 shows both cases. This is the simplest implementation strategy to let the user be aware about the exceeding consumption. The power limit can be set using the scroll-bar. In the W2W proof-of-concept described in Section 5.1, the power limit value is sent to the SP as well. When the power consumption exceeds the limit, the SP starts buzzing.

Now, let us consider the second release. Figs. 5.12,5.13,5.14,5.15 show a snapshot of the GUI. As we can see, the GUI shows four tabs. The instantaneous total power consumption and the corresponding cost[4] (Fig. 5.12) are displayed on the “Aggr” tab, while the instantaneous power consumption of each device connected to the SPs and the corresponding cost of energy are displayed on the “Disag” tab (Fig 5.13). The “Disag” tab also allows to specify the appliance connected to each SP through a list box. If the device is not present in the list, it can be simply added by typing it. The information displayed in the “Disag” table allow the user to get a perception of the cost of electricity and to see whether a waste of energy is in act. The “Yesterday” tab (Fig. 5.14) shows the total energy consumption of each device and the corresponding cost for the usage during the whole previous day. This information is very useful, since it allows the user to understand the cost of employment of each device. As an example, the user could be curious to know the cost of the cycle of the washing machine that he has used during the previous day. Finally, the “Settings” tab (Fig. 5.15) allows for setting the energy tariff (from a list box or by typing them) during daylight and night hours. This functionality is useful in Italy where different tariffs are offered, depending on the hour of the day. The “Settings” tab also shows a Reset button that can be used to delete the list of devices connected to the smart plugs.

[4] In order to compute the cost, it is assumed that the power consumption remains constant for one hour.

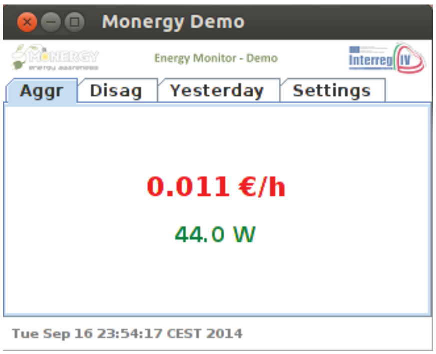

Figure 5.12: Java GUI: Instantaneous aggregate power consumption and corresponding energy cost.

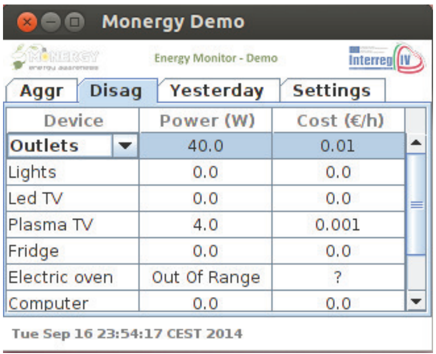

Figure 5.13: Java GUI: List of appliances with instantaneous power consumption and energy cost in Euro/hour.

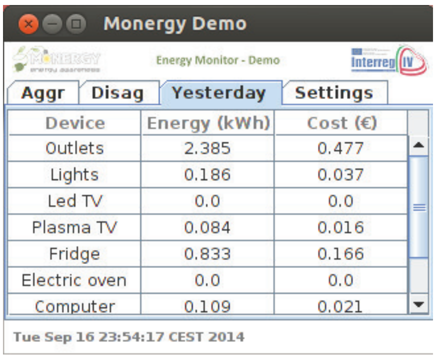

Figure 5.14: Java GUI: List of appliances with consumed energy and cost of the previous day.

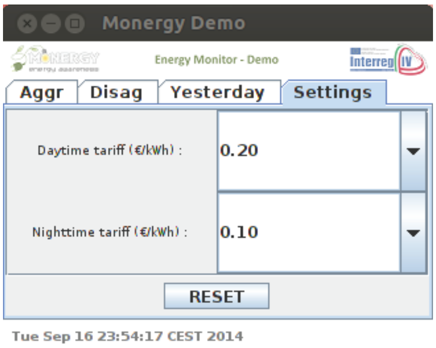

Figure 5.15: Java GUI: Settings tab.

Conclusions

This deliverable has presented the work carried out within WP4 of the Monergy project.

The Monergy HEMS has been presented. It is composed of a set of SPs connected through a Zigbee interface to an SHG that has been developed on an ARM platform. The SHG is capable of sending power consumption measurements data to the Monergy servers. Power consumption data is displayed on a web page, and can be downloaded in CSV format.

The Monergy HEMS has been installed in 9 households deployed in Carinthia and Friuli Venezia Giulia to monitor electrical appliances. Data gathered from the monitoring campaign has been publicly released by means of the GREEND dataset.

Experimental HW and SW improvements to the Monergy HEMS have been presented. In particular, a wireless to wireline proof of concept gateway that allows for having a hybrid network whose SPs can adopt wireless Zigbee or power line communication interfaces has been presented. It allows for solving coverage problems experienced by the use of HEMSs that adopt Zigbee communication interface. Furthermore, in order to solve installation issues related to the monitoring of aggregate power consumption, an aggregate power meter that can be mounted on a DIN rail module has been developed. It may also allow to implement non intrusive load monitoring algorithms. Eventually, a graphical user interface that is suitable for being visualized on a small screen display has been also presented.

In the next months, the results of WP4, and in particular, the GREEND dataset will be used within WP5 to derive energy usage profile of inhabitants of Friuli Venezia Giulia and Carinthia so to derive commonalities and differences and to give practical information to save energy.

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