Wireless Sensors Solution for Energy Monitoring, Analyzing, Controlling and Predicting

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Abstract. The work presented in this paper addresses the problem of energy wastes through irresponsible usage of computers or electrical devices, as well as wastes encouraged by companies or firms that do not implement any kind of power awareness plan. It is meant to help increase the power usage efficiency in the locations it is installed, by completing an extensive survey of power usage patterns over a short period, and then presenting clear expressive power consumption results of the monitored location, together with recommendations of action plans that would save energy if applied. Based on the consumption analysis, studying energetically profiles for different electrical devices, prediction of power consume and savings can be made. We propose a new wireless sensor network solution that can be used to profile power consumption of both electric power connected devices and battery-powered devices running different applications. The proposed solution offers a better and easier way to monitor the energy each of the target devices, and get real time feedback on the effect of different usage patterns applied to target devices.

Keywords: power consumption, power characterization, power profiles, power signatures, wireless sensors network.

1 Introduction

The information and communication technology industry is responsible for 2% of the global carbon dioxide emission. The figure is equivalent to aviation industry [1]. In Europe, the energy consumption in data centers was 46 Terawatt hours, in 2006, and 70 Terawatt hours in USA in 2007. This is the equivalent of one hundred million 100 watts light bulbs running 24 h/day 365 days [2]. Moreover, a reduction of the energy consumed by the IT equipment has the greatest impact on overall consumption, because they cascade across all supporting systems [3].

Another aspect of the problem is the high energy consumed in data centers. Gartner's research showed that data centre and IT managers are interested in internal projects like rationalization and virtualization. In order to achieve improvements in

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the energy efficiency for data centers, it is necessary to gain a better understanding of server power consumption and how does this influence the server performance [4].

As far as household domain is concerned, in 2006, BBC predicted that irresponsible behavior of home users in UK would cause an emission of carbon dioxide of 43 millions of tones by 2010 and a cost of £11 billion, coming only from electrical energy wasted during this time [5].

Therefore, important institutions like The European Parliament discussed about reducing energy waste and new standards for standby power consumption of electronic devices [6]. The European Union action plan to increase energy efficiency is oriented also on changing energy behavior of the consumer, public awareness being one of the priorities [7]. Besides the European Parliament, other important institutions (as the European Commission, the Economic Committee etc.) have participated in an awareness-raising campaign on energy saving 'M'illumino di meno' (meaning ‘I'm using less light’) on 12th of February [8]. This action shows their interest in reducing energy usage, by eliminating energy waste.

Only advanced monitoring, modeling and measuring techniques would lead to an effective energy management [9]. A system to monitor the electrical consumption of individual devices in a home or office buildings could help people make decisions that are more informed on how to alter their usage patterns and choice of electrical devices in order to conserve electricity. This detailed picture would help users better identify those devices or usage patterns that are leading to needless electricity consumption.

Therefore, we propose a system to monitor, analyze and control the energy consumption of individual devices in a home, office building or data centre could provide the necessary tools that lead to a superior energy management. The proposed solution is a better way for individuals or companies to see how much electricity each of the devices in their homes and offices consume, to make a prediction based on consumption habits and try to control the amount of electrical energy that is used. One practical aspect of our solution is that the user can receive a more detailed feedback on the energy used by receiving an electric bill with a line for every individual device that details how much electricity that device used over the monitored period and shows a graph of the power consumption through time.

We aimed our system to be a configurable one, which takes into consideration the three types of users (office buildings, data centers, home user), and their particularities:

- In office buildings, the energy waste can be reduced by offering a system that monitors and controls the energy consumption. A simple action, as shutting down PCs at night saves $15 to $20 per computer annually [10]. Office buildings are characterized by a large number of systems of the same class, usually desktop computers that have the same kind of usage profile. Therefore, electrical and computing devices existing in office buildings need various profiles according to the companies working program in order to optimize energy consumption according with their weekly program. Every such profile offers the needed level of usability for the devices at the minimum energy, hence energy efficiency could be obtained;
- For data centers we want to offer a less expensive solution that monitors and analyses consumption at different levels (server level, cooling system etc). We are

motivate by the fact that in the present, there is a lack of detailed information about power consumption at the rack or row level [11]. Therefore, without an accurate measuring, there is no basis for trying to optimize data centers [10]. Data centers equipments are characterized by high availability under different load levels, therefore the existing power management solutions must not influence the quality level of the services they are implemented for. One possible solution in such environments is to use the proposed system in order to implement a dynamic balancer between virtual machines and physical machine in order to obtain optimum energy efficiency for the current performance and quality requested level;
– As for home users, we propose a solution that will make people aware of their consumption habits, helping them reduce costs and try to make them more responsible. Home buildings are characterized by a much larger variety of electrical, electronic and computing devices: TV sets, DVD Players, desktop and laptop computers, washing machines, air conditioning, refrigerator, microwave, radio sets, etc. This variety of devices implies a variety of power signatures and usage patterns which makes the energy consumption uncontrollable [12]. The most important aspect for home usage energy efficiency is to identify users' bad habits and to make them aware of their effects.

These goals can be achieved by means of four actions implemented as core features in the proposed solution: monitor, analyze, control and predict.

– monitor feature permits online measurement of all or targeted devices in order to save power consumption, voltage and current consumption values into the database for further analysis and to provide a real time image of instant overall or particular device power consumption;
– analyze feature provides a way to extract relevant data from the measurements existing already in the database. This module offers a number of various reports and charts that show different perspectives on overall or specific energy consumption for certain period of time;
– control feature is an important mechanism to programmatically switch on or off specific devices according with its class or usage profile. However, some problems may appear when controlling certain devices, like computer systems, because of their specific shut down process in order to avoid data loss;
– prediction is needed mainly for dynamic power management implementation in order to select the correct management decisions in order to optimize the overall power consumption under certain requirements. Prediction can be implemented as long term and short term trends generation starting from measurements stored in the database.

In this paper we describe in Section 2 the other actual work related to the domain addressed in our project. The overall architecture of the power consumption monitoring solution is presented in Section 3. The solution architecture contains both hardware and software solution design. In Section 4 the power signatures of electrical devices are introduced together with their characteristics and the example and discussion of the extracted power signatures for one type of electrical device. The conclusions are presented in the last section.

2 Related Work

Reducing energy consumption of electrical devices has both economical and ecological benefits, but it also opens new research directions related to the interpretation of power consumption data. The research directions we are interested to explore starting from the power consumption monitoring of various devices are: energy and power signatures definition and their characteristics; the relation between usage patterns, power profiles and energy signature; and new application-aware power management techniques for energy efficiency. In this section we first discuss current tools for monitoring electrical consumption then we present some research papers which address power and energy monitoring and analysis.

Although there are a number of options for measuring power consumption at the level of a total building (the electric meter being the most obvious), a cheap scalable option for measuring power consumption of each device individually does not exist [13]. The current way one can measure power consumption of an electric system is to use an on-the-self device like Kill A Watt [14] or Watts Up Pro [15]. Both of these features make it difficult to develop a practical real time system specific picture of energy usage that contains many individual devices because the user must go to each monitor in order to record the data [13]. Most of the available solutions [16] are oriented on consumer market therefore they do not offer complex features and power management support or integration. On the other hand, professional solutions oriented to servers and network equipments in data centers are expensive and they are oriented mainly on alarms and failure avoidance, but they are not used for dynamic power management. In [16] there are presented ten energy monitoring tools: EnergyHub, Tendril, Onzo, Agilewaves, Google PowerMeter, GreenBox, The Energy Detective, PowerMand, Green Energy Options, and Energy Aware. It is out of the scope of this paper to present and compare all these devices, but [16] is a good starting point to explore these solutions.

The author of [13] proposed an electrical power monitoring system containing distributed units that transmit power consumption data wirelessly via RF radios to a central base station. The designed monitoring units plug into an outlet and then the device being monitored is plugged into them. The base station parses the incoming data from multiple monitors to determine the power consumption of each device in order to have an overview on overall power consumption. Our solution is similar with the solution described in [13] in terms of hardware overall architectures but it much more oriented on the four core features implemented in the software (monitor, analyze, control and predict).

In [17] the authors proposed to implement a virtual instrument for the electric power quality monitoring aiming to act in real-time for detecting, monitoring and recording all typical disturbances superimposed on the ideal signal. Their goal is to extract the voltage and power quality parameters for the power distribution network. The authors present a completely digital method for the fast and accurate monitoring of the electrical power quality useful to produce real time quality/ disturbance reports. In the paper, the mathematical basis of the proposed estimation algorithm is discussed in terms of reliability and uncertainty. This work is different from ours because we do not address the quality or disturbances of power lines but we consider the power signatures and their relation with the usage pattern of the device.

An interesting idea is presented in [18], where the authors try to find a way to obtain detailed information about electricity consumption in a building, at a low cost, without the usage of distinct power meter for every target device. They intend to achieve this goal using a non-intrusive method, maximizing the use of the existing infrastructure rather than imposing the need to install various new devices in the building, thus reducing the associated hardware and labor costs. In order to split overall power consumption data they built a data acquisition system that samples voltage and current at 100 kHz and calculates real and reactive power, harmonics, and other features at 20Hz. The authors showed that under certain conditions disaggregating the total power consumption between different plugged devices is an achievable task, and can be done with a relatively high degree of accuracy. However, the problem is much more challenging in the real world, where not only does the number and type of appliances increases, but also the measurements are susceptible to more noise and obtaining ground truth data becomes more difficult [18]. Furthermore, they did not take in account complex devices, like computers, which do not have constant levels of power consumption, but it varies significantly with the running applications.

The original aspects of our work are: identification of specific aspects of different types of users power consumption patters and their energy management requirements; definition and implementation of the core features required by a complete energy management solution; definition of power signatures and their relation with the usage patterns; design and implement the extensible and cost effective wireless sensors network and software application for power consumption monitoring, analysis, control and prediction.

3 Solution Architecture

The proposed solution aims to address a wide range of needs in this domain, and that was the starting principle in the design process. We have to take into account different usage scenarios in order to satisfy as many requests as possible. Also, given the use of the wireless sensors, the topology of the location has to be accounted for. That is why an incremental design process was selected, which allows for developing a base solution which serves only a small segment of clients, and then extend it with more functionality at each step. We started with addressing office buildings, which present a high density of computers and workstations. There are two advantages in this approach. Firstly, the types of devices to be monitored do not vary considerably, because all computers can be abstracted to a one-phased AC powered device. This means that the hardware needed in the implementation of this solution is the same for all devices, which lowers the development costs. A second advantage is represented by the fact that there are many devices to be monitored in such locations, in comparison with home or industrial locations. This stresses the software, because more data is processed and transported through the system at each architectural level. The added strain on the software part allows for a more reliable development process, because more code is covered and exercised at a high load, so the faults are caught earlier and the final result is more reliable.

The development process for this project carried us through many knowledge domains, from electrical engineering and computer network principles to database management, web design and event-based programming. We faced challenges in developing different parts of the system and were able to learn as we advanced through the design. The software development has different characteristics, depending on the level of the system it was done for. The low-level code for the microcontroller from the sensor nodes was written in AVR Studio development environment. This environment was chosen because it allows writing the code to the micro-controller's flash in the same interface. Plus, it offers a real-time debugging option. Both this characteristics provide a faster development process and testing of the written code. The code for both the eBox and the server was written in C# using the .NET platform and Visual Studio 2010 Professional. The difference resides in the type of the projects. The user interface web application on the server is an ASP.NET MVC 2 project because it uses the model-view-control design pattern. The Windows Communication Foundation was used to assure the communication with the server, thus WCF projects were created separately for the eBox and for the server and the IIS service was activated. The rest of the functionality of the code on the eBox is integrated in the mentioned project and addresses Xbee communication, the configuration module, data base administration and the data processing modules.

3.1 Hardware Architecture

In Figure 1, we designed the overall architecture for the hardware of the project. This design is built around the eBox which is considered the central embedded element of the system. This is a ready built device and no hardware alterations were done to it. Together with the sensor network coordinator, the eBox forms the central unit. The interface between the two is implemented through a USB port. Also, the components of a sensor node are specified in the figure. These are the Xbee module, an ATmega16 microcontroller and the measuring device adapted to the type of element which needs measuring. As far as the server is concerned, the hardware represents a normal Windows Server 2008 machine. The custom hardware components used in this project are further detailed in this section.

The hardware layer of this project is mainly represented by monitoring devices with wireless communication capabilities (Figure 2), whit each device being connected between the AC line and an electrical consumer. These devices together form a sensor network designed to measure the power consumption and AC line parameters within an office building, a datacenter or a personal home. The wireless sensor network is responsible for acquiring power measurements from the devices attached to the AC line and transmitting them to a central unit. Each node is composed out of a controller specialized in measuring AC line parameters such as voltage, current, active power and frequency, a wireless communication device and a microcontroller which controls the whole activity of the device. Besides measurement capabilities, each node has a secondary task such as routing the information to the central unit. Each measuring node is identified through a unique serial number provided by the wireless device.

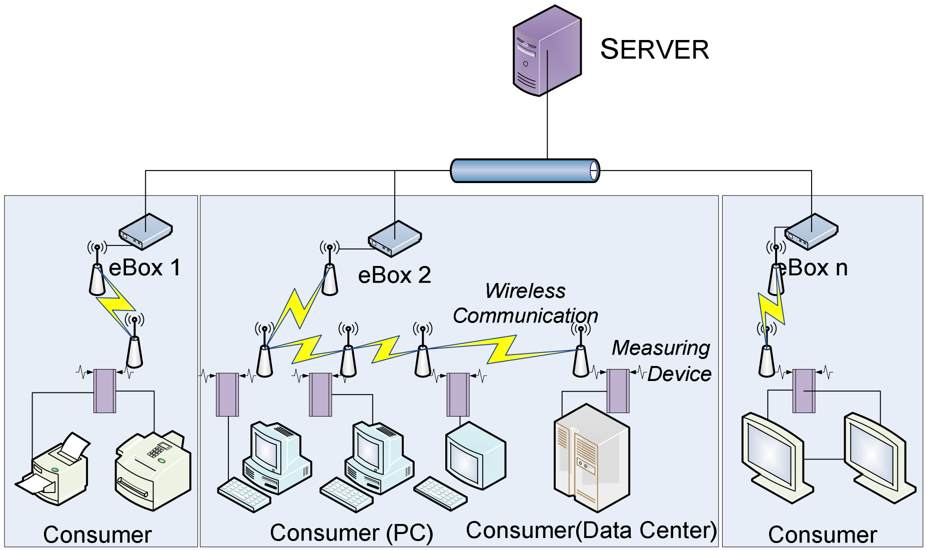


Fig. 1. Overall solution architecture

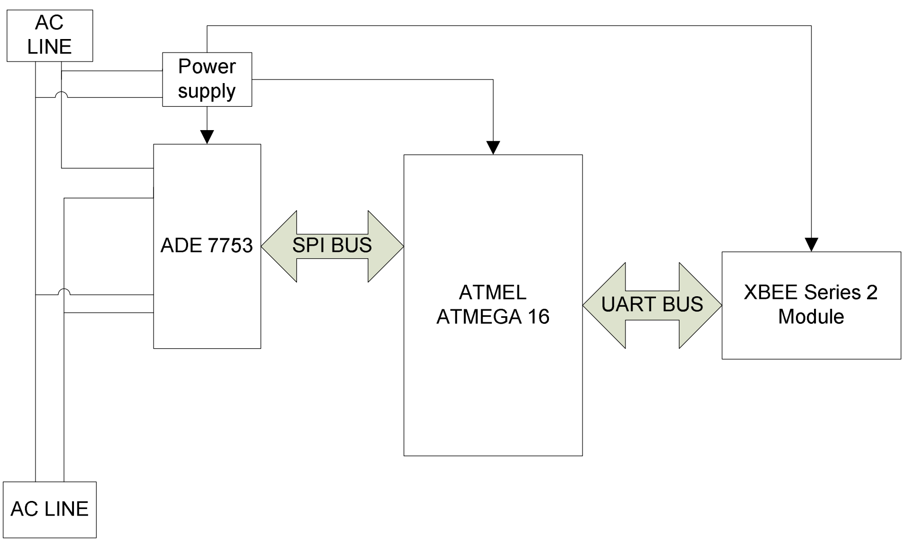


Fig. 2. Measuring device architecture

3.2 Software Architecture

The product is structured in three separate stand alone applications:

– the EBox component which can collect data from the sensors and also control them;

– the Web portal which can be used to represent data in a logical and friendly fashion;
– the Web Service which holds the logic to access and modify the data for outside consumers (clients) for example the EBox.

All was centered around the data logic and modeled as a separate project with logic shared between the other components (service, reports, web portal, admin applications). As a development platform we used .NET 4 with its enhancements for Entity Framework and ASP MVC. For modeling the data layer it has been used Entity Framework 4 and Unity 2.0 in order to assure a persistence and context ignorant scenario for each application this was deployed to. Persistence ignorance was assured by POCO objects (a feature introduced in Entity Framework 4) while the context “ignorance” was handled by making use of Dependency Injection found in Unity 2.0 Framework.

On top of this came the service with its logic to access and modify database sensible content. The Service was done with WCF and if the client supports WS Binding, than it can make use of sessions (different instance/session) enabling caching and logic enhancements. The Website was meant to provide frontend business capabilities and was developed with ASP MVC 2.0 making also use of the same logic as the service. Rich client graphics and effects were accomplished by using jQuery with some of its famous controls/plugins (apple like menus, tabs, grids) which we enhanced to support different business scenarios for example paging in grids, autocomplete in comboxes.

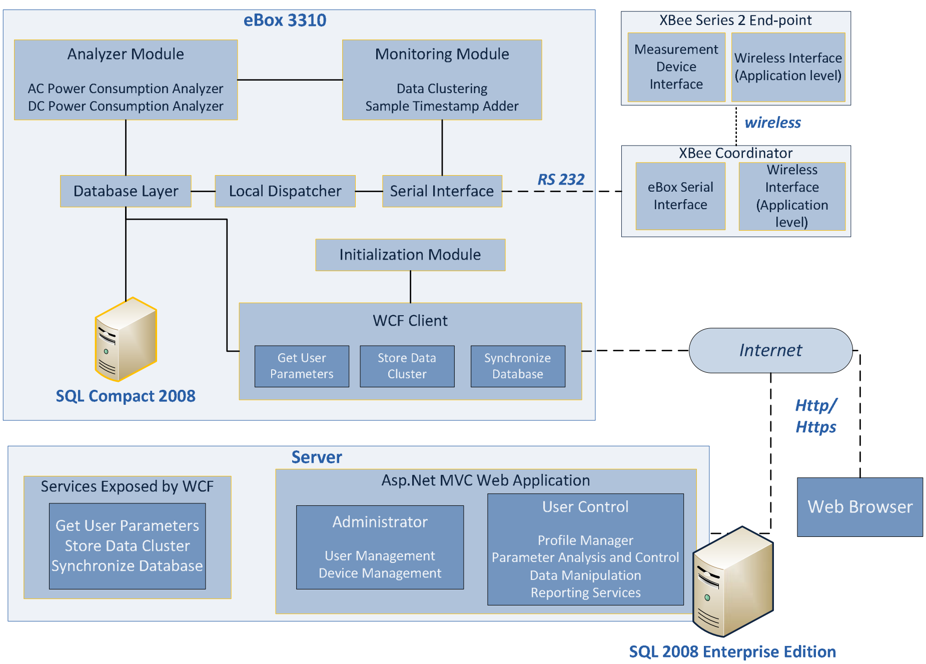


Fig. 3. Overall software architecture

The software part of the system is described in Figure 3 [12]. As mentioned before, the various components follow the general system architecture, with the code on the eBox being the one offering the main functionality. The applications written in different levels of the system have distinct characteristics and are described below. First, we first have the low-level code that is written for the microcontroller in the sensor nodes. There is a separate part that regards the coordinator. This consists of the serial communication protocol for the connection with the eBox. The code on the endpoints differs from the one written to the coordinator, because the controller on the endpoint has to communicate with the measurement device and read data from it. So, the serial interface is replaced by the interface with the devices. Both types of sensor nodes implement a communication protocol between them, which builds on top of the already existing layers. Second, we have the software on the eBox, build on top of a Windows Embedded 6.0 Image. The eBox gathers all data from the monitored devices and stores it using the compact version of SQL Server 2008 for embedded devices. A monitoring module congregates data into clusters of measurements coming from the same source and adds a timestamp to make chronological ordering possible.

Then a mild analysis is done to remove inconsistent data from the clusters, such as misreads or values that could not practically exist, but are reported due to specific events in the power line, especially in alternative current. After the analysis, the data can be stored into the database. After the analysis, the data can be stored into the database. In this state, the data is structured into chronological data samples from the same source, and each source has its own data. Reporting and analysis features were provided by Microsoft's Reporting Services 2008. Data was stored in Microsoft Sql Server 2008 R2. Though not implemented yet in the web portal, support for localization (example Bing Maps) it's present.

The database structure we designed is presented in Figure 4. There are a number of 15 tables that resulted from the normalization process. We have a table-cluster that represents the hierarchical representation of an organization (company-department-locations (rooms)) and a set of corresponding maps for each location. On the other side, an abstract representation of physical elements can be seen (monitored device, eBox, consumption). The central tables are the user table, which can access identity, rights, location, consumption and devices information. For security reasons, the password field contains the md5 code of the user-selected password. We used this encryption for its proven correctness and safety in many domains and applications. In this way, the only place the password itself is available, is the login form textbox where the user enters it. Each device has an ID, from the XBee unique serial number, the name given by the user, the name of the location it measurement entry has a timestamp, the values of the current and voltage from which the power will be calculated, and a reference to the device that provided this measurement. The same structure is available on the data base present on the server. For the communication to the server, Windows Communication Foundation is used. The server makes available through WCF several services regarding the data transfer. One service assures that the two SQL Servers present in the system stay synchronized. Another is used to communicate to the eBox which devices from the user's list are enabled and which are disabled. The third service permits the eBox to upload the clusters of data to the server.

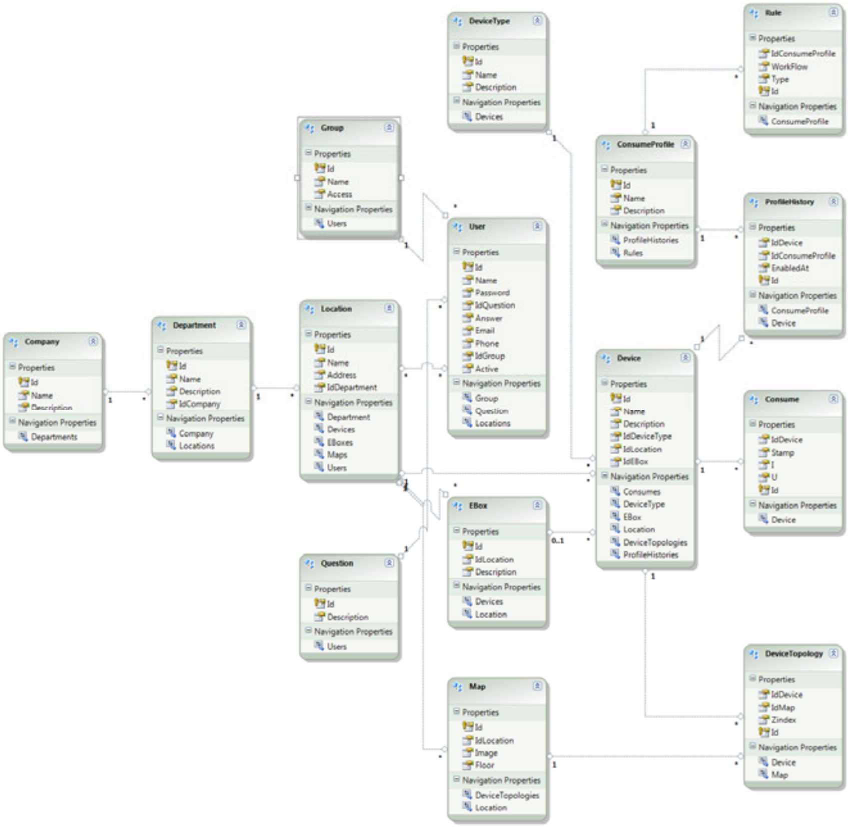


Fig. 4. Database architecture

The security measures taken at this point are described next. First, the communication through the WCF is done using https with a self signed certificate, for the moment. More important, at each access from the eBox to the server, the registration protocol is used, meaning that the username and password stored in the data base of the eBox are transmitted to the server. Only after the data is checked, the server allows the communication to start. If the provided username and password are found in the database on the server, but the eBox serial number is not present, the system assumes that a new eBox was added for the specified user, and registers it. Finally, there is the software running on the server. This is split into two parts. One consists of the discussed WCF Services: synchronization and data storing operate with the local SQL Server, while the user-parameter setting transmits to the eBox the user preferences. The second part is a web application that addresses the users of the system. This application is designed using the model-view-control pattern available in ASP.NET. The data regarding the current user is loaded from the global data-base containing measurements from all users and is stored in the model. Then, when the user requests certain information to be displayed, the controller enables the view containing the respective data. There is a view for the list of devices, and one for each of the devices, with the graphical representation of the consumed power over a period of time.

3.3 Analysis and Prediction

Analysis and prediction are two of the four main functionalities of our solution. Moreover, they are the ones that mostly influence the user into changing his behavior. Analysis offers the user 4 various graphical representations of the consumption of one or more devices.

– A first option would be to generate an intuitive graphical representation of the consumption of all devices in a selected location, over a defined time span. The total consumption is depicted with the help of bar charts.
– Another chart will show the consumption distribution for a selected location, highlighting the contribution of each device to the locations total power draw. If, for any reason, a device is responsible for a major proportion of the consumption, the user might understand that he is misusing that certain device.
– Third, the user can generate an individual consumption distribution pie-chart showing how much time the selected device spends in each of the four consumption categories: low-power, normal mode, high and very high. The pie-generation algorithm is straightforward: having the minimum and the maximum consumptions over the selected time interval, all consumption readings (in Watts) are attributed to one of the four categories by the following criteria:

```
interval = maximum – minimum
if (Watts <= interval * 0.20 + min) -> low-power (0-20%)
else if (Watts <= interval * 0.60 + min) -> normal mode (20-60%)
else if (Watts <= interval * 0.80 + min) -> high mode (60-80%)
else -> very high consumption (80-100%)
```

– Finally, a classic XY chart, showing the consumption evolution over a selected time span, can be generated.

Note that, if, for instance, the user selects a very broad time span, it will be automatically narrowed to the space in which readings have occurred, so that the representation area will be filled by graphics. All four analysis graphics can have their representation step set to a day, week, month or a year.

Prediction is again, a simple yet powerful tool, which will offer the user an insight on the possible consumption evolution over a selected period of one day, one week, one month or a whole year. Of course, the accuracy will depend on the amount of data has already been collected. The generated report or graphical representations are based on the same algorithm:

– All (W) readings are clustered into groups corresponding to the prediction range (e.g. if “weekly prediction” is selected, all readings for the selected device will be grouped into clusters for each week up until the last finished week)
– For every cluster an average consumption is computed for each temporal subunit (e.g. for “weekly prediction”, the subunit is day. An average consumption will be computed for each Monday, Tuesday … Sunday. The subunit for day is hour, for week day, for month week and for year it’s a month).
– In order to predict to consumption for each temporal subunit the following computations are done:

```
N = number of available subunits with recordings
Next subunit possible average consumption =
          {subunit (N) - [subunit (N) - subunit (N-1)] / 2 +
          average (subunits)} / 2
(E.g. we have the following consumptions: Monday (N) = 100W, Monday
(N-1) = 60W and overall Monday consumption M = 70W.
We need Monday (N+1), which equals [100 – (100 - 60) / 2   + 70] / 2 =
(100 – 20 + 70)/2 = 150/2 = 75 W)
```

As can be seen, the prediction algorithm focuses on the idea that our consumption habit for the next tine interval depends on the habit over the last two intervals, and is further approximated with the help of the overall average consumption habit.

3.4 User Features

The targeted clients of our service have very different profiles, from company managers or representatives, who want to reduce power consumption in a certain branch, to individuals who want to analyze the energy consumption in their homes. That is why we designed the solution to require less training on the user part and not to rely on any previous knowledge other than internet browsing. After this step, the system is powered on and the client only needs an internet connection to access the server and use the application. The user interface presents a list of all the registered devices for the logged in user. The device name and id are displayed, together with the power consumed by the device since the start-up of the system, both in absolute values and in percentages of the total power consumed.

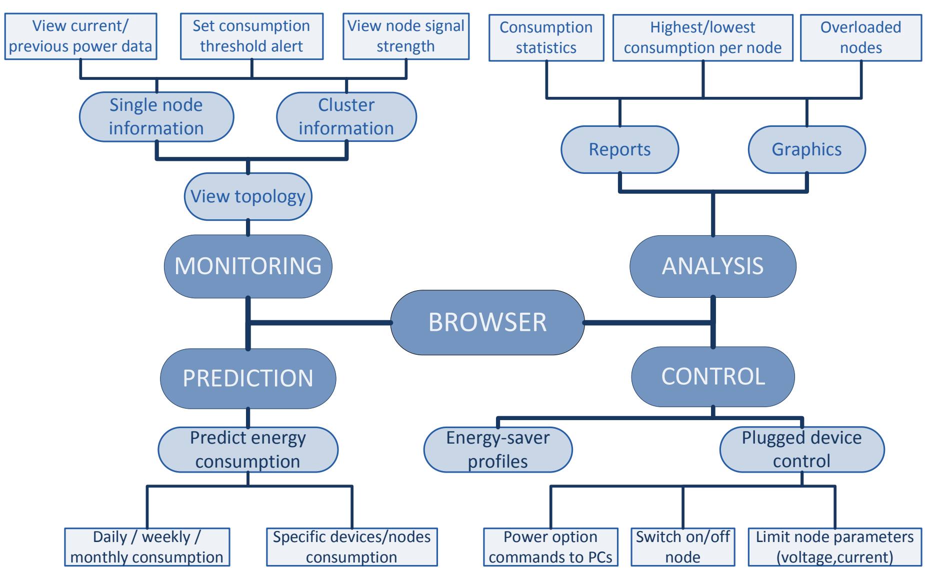


Fig. 5. Features overview

Any user may opt for one of the four main functionalities (depicted in Fig.5) supported by the user interface (Fig. 6). The monitoring option offers a 2D spatial view of the installed network of plugs. Interaction is possible with all nodes, and data may be obtained from them in the form of reports or suggestive graphics. The prediction option is a special asset which may give an idea regarding, for example, the value of the next electric bill. The control option enables remote on/off switching of specific consumers and offers the possibility to apply a certain energy-saver profile. These profiles take decisions like turning off lights at night or putting a PC into hibernation.

Action	Stamp	I	U	Device	Location	Department
Show Details	5/14/2010 7:16 PM	2.64	32.76	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	3.13	36.32	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	3.21	24.22	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	2.92	37.51	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	2.41	32.81	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	2.04	31.79	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	3.25	28.15	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	3.22	32.82	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	2.97	39.09	Device_6 (#6)	B520	Calculatoare
Show Details	5/14/2010 7:16 PM	2.85	32.83	Device_6 (#6)	B520	Calculatoare

Fig. 6. Graphical user interface

4 Power Signatures and Test Results

4.1 Power Signature Definition

Power signature of an electrical, electronic or computer device is defined as the power consumption response to certain workload executed by the target device. Power signature is the variation in time of power consumption measurements when certain usage pattern is applied to the device. Some devices can show distinct power signatures function of the type of workload the device executes or function of the applications executed on the device. Therefore, power consumption of a device is not constant but it depends on various hardware parameters and user applications. Test methodology we used to extract power consumption signatures addresses two directions: the power states of target devices and the usage patterns of top level applications. Every device has at least two power states (on and off) while most devices implement more power states: off - the device is turned off, but it remains plugged in; sleep or stand-by - the device is in one of its power saving states, where it waits for certain commands to switch in active state again. In sleep states a device is not completely switched off in order to retain at certain level the last active device state or context, so that the active state can be easily activated; active - the device is turned on and executes its activities. The application level influence on power consumption is much more difficult to model but it has an important impact on the power signature.

Considering the relation between type of workload executed by certain device and its power consumption variation when executing the workload, we grouped the consumer electrical devices in three classes:

– Low-intelligence devices are considered the systems whose power signatures depend only or mostly on the hardware power states the device passes through when used. In this class we include consumer electrical devices like: refrigerators, washing machines, heating devices, air conditioning devices, etc. For these devices their power signatures are less influenced by their usage parameters or workload type they execute.
– Medium-intelligence devices are considered the systems whose power signatures depend on both hardware power states and the workload the device executes. In this class we include the electronic devices containing some level of electronic control features: TV sets, radio devices, CD players, DVD players, set-top-boxes, fixed phones, etc. The power signatures of these devices are moderately influenced by the workload they execute.
– High-intelligence devices are considered the systems whose power signatures depend mainly on the workload type and parameters they execute. We include in this class the computing systems containing at least one certain type of central processing unit like microprocessors or microcontrollers. In this class of devices we consider: desktop PC, notebooks, PDAs, SmartPhones, printers, network devices, etc. The power signatures of these devices are strongly influenced by the workload they execute.

For every type of device which can be seen as power consumption source we can establish different power signatures (or power fingerprints) which denotes the power consumption of the device for a given utilization profile (e.g. usage pattern, applied stimuli or workload). In our tests we observed that every electronic device has a specific power consumption profile for different workload type or usage patterns [12]. We started from the results obtained in [12] and we tried to identify the power signature characteristics and their benefits, and we take in study one simple device.

4.2 Test Workbench

The performance criteria by which we benchmarked our system refer to specific metrics depending on the component being analyzed. The system as a whole has to be accurate, fast and scalable. During the tests, we observed the behavior of our system, paying special attention to faults occurred in the components of the system. The communication distances between two XBees were measured. In open space these were of about 30 meters. When the modules are separated by a 25 centimeters thick concrete wall, the communication between them is interrupted. On the other hand, a thinner wall, of 15-20 centimeters, only shortens the distance to about 10 meters. Glass doors do not affect the communication in any way, which is a good thing especially when using the system in office buildings. Regarding the transmission times, these are satisfactory, especially because we need to transmit a sample from a device every five minutes. This allows for enough time to gather measurements from all devices present and due to the processing power of the eBox, the samples are analyzed and stored in time, such that the workload on the eBox is not at constant high levels.

Considering all these parameters, we tried to execute the tests in the same environment. For every type of device we considered specific set of tests in order to extract power signature characteristics. We tried to see two aspects of power signatures: whether they are the same or similar when executing similar workloads and second, whether they are distinct when executing different workloads. In our tests we considered one programmable device in the first class - a washing machine.

4.3 Test Results

The first test was executed to identify the elements of the washing program and their effect on power consumption. There are seven phases of a complete washing program (Figure 7):

- (I) - the prewashing phase;
- (II) - water heating phase (40^{o}C);
- (III) - first washing phase;
- (IV) - an optional heating phase between the two washing phases;
- (V) - second washing phase;
- (VI) - rinsing phase;
- (VII) - drain and drying phase (1000 rotations/minute).

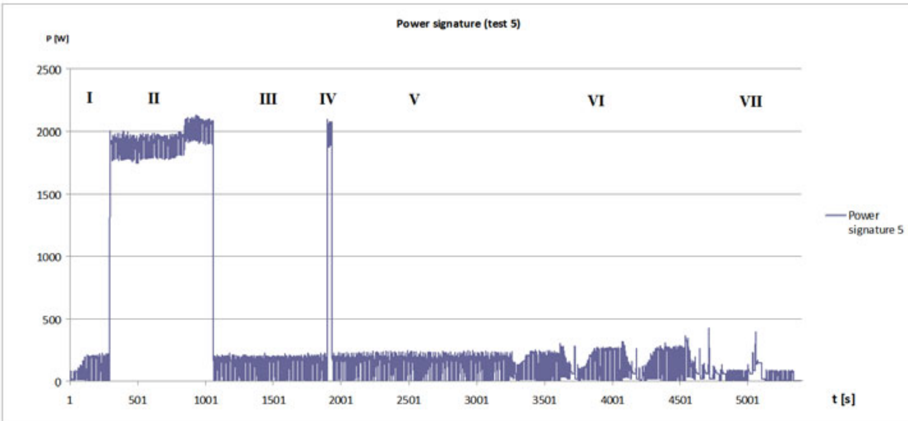
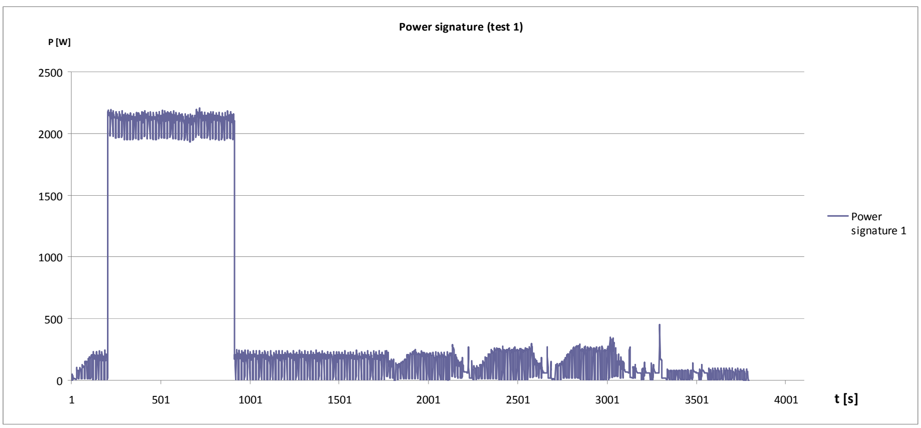
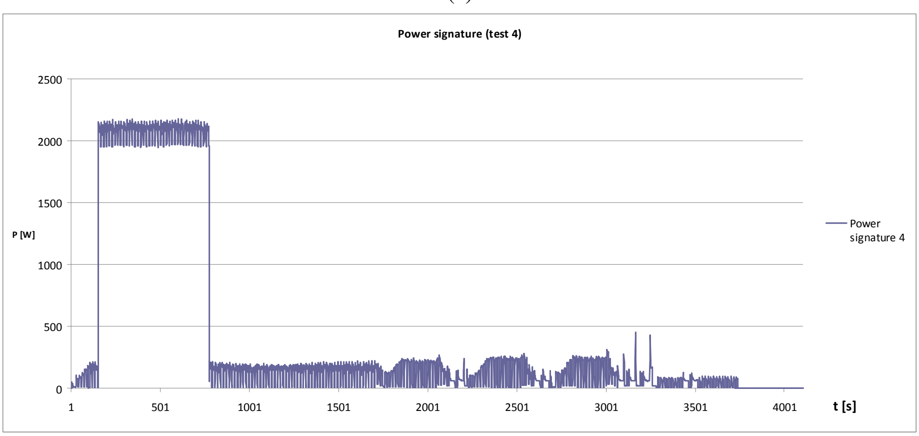


Fig. 7. Washing program phases and their power signatures



(a)

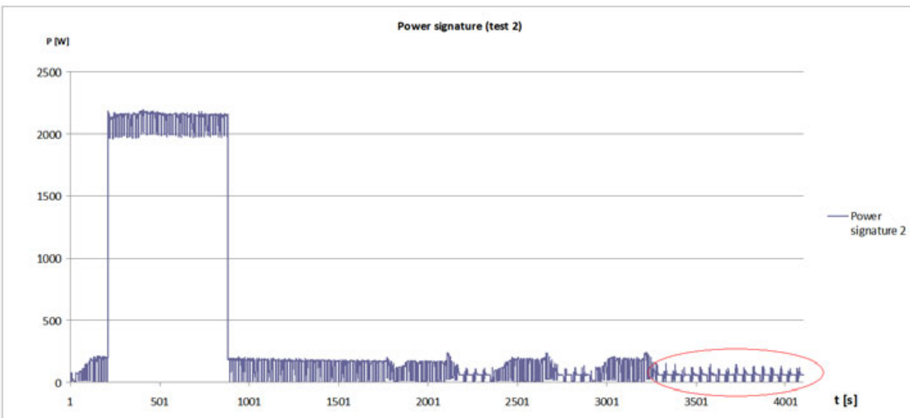


(b)

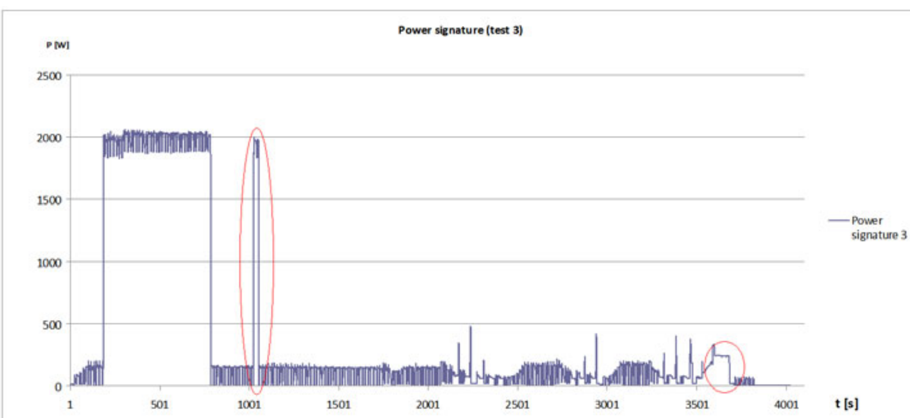
Fig. 8. Power signature repeatability

The second test emphasis the stability and repeatability of power signatures when running the same washing program and the same clothes workload. We run the washing program four times and we monitored the power consumption (Figure 8a). The obtained power consumption signatures were the same, but some differences can be observed due to different amount of items washed. During test 4 there washing machine was loaded half of its full capacity therefore the heating phase is shorter because the washing machine automatically adapts to the workload (Figure 8b).

During the test 2 we observed that the washing machine didn't drain the clothes correctly. This malfunction can be observed in the power signature in Figure 9 (a). In Figure 9 (b) two differences are observed compared with standard power signatures: an extra spike to heat the water between washing phases and a larger drain phase. In our tests we obtained both similar signatures for similar programs and workloads and distinct signatures for different programs or workloads.

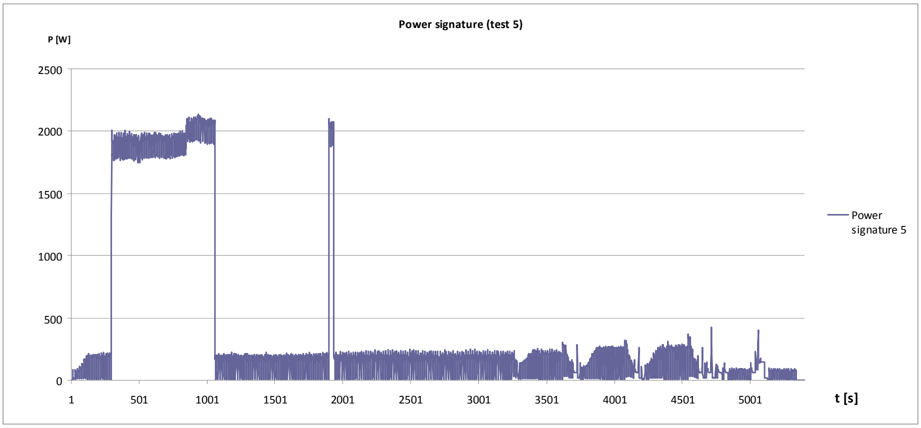


(a)

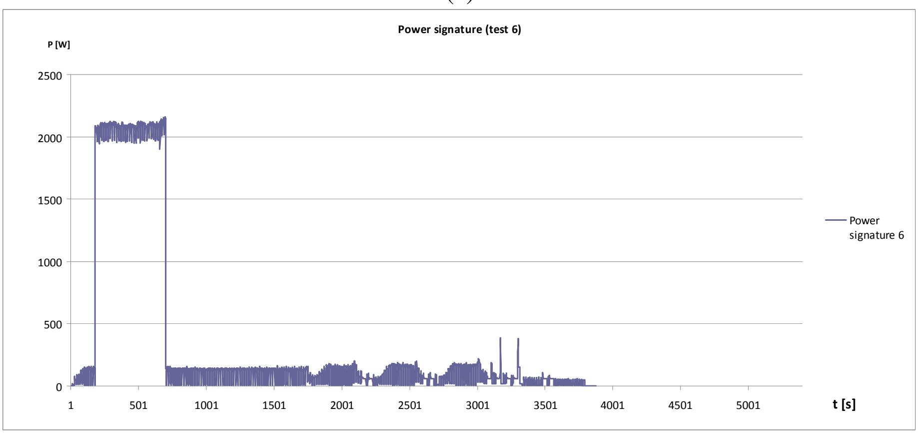


(b)

Fig. 9. Power signature differences



(a)



(b)

Fig. 10. Washing programs power signatures

In Figure 10 two washing programs power signatures are presented. In Figure 10(a) there is a long program with full capacity loaded and the second chart depicts the power signature of a short washing program with only half of the capacity loaded. It can be observed in Figure 10 (b) the shorter heating phase duration due to the smaller quantity of water needed in test 6. It can be also observed the missing of the washing phase I in test 6, and this is specified in the selected washing program.

6 Conclusions

In this paper we presented our proposed architecture for online monitoring of different consumer electronic devices. We defined the concept of power signatures of different types of devices and we run a number of tests for a device in every proposed class. Based on these preliminary results for every power signature class further specific analysis can be done in order to observe usage flaws and malfunctions of the devices. For certain types of devices, power signatures can be used to monitor the usage pattern of that device and furter power management assumptions can be made.

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