Controlling electrical home appliances, using Bluetooth Smart Technology (October 2015)

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Abstract—This report presents and describes a Home Energy Management system that accomplish Home Automation with energy efficiency, where Bluetooth Low Energy is responsible to support communications inside the house. Bluetooth Low Energy is a power-friendly wireless technology design to send small data packets when needed and then puts the connection to sleep during periods of non-use.

A workable prototype of Home Automation was set-up inside a house. Bluetooth Low Energy demonstrated to be a possible solution to implement the required bi-directional communications. This prototype allows the homeowner to control his home system through BLE android App, running on a Smartphone with Bluetooth 4.0 version, and through internet.

Index Terms— Home Automation, Smart houses, Energy Management, Bluetooth Low Energy.

I. INTRODUCTION

Home Automation (HA), a technological evolving subject, permits to improve, comfort, security and energy efficiency at home. Smart houses use Home Automation systems where the homeowner or pre-defined algorithms, controls home equipment (lighting, air-conditioning, home appliances, doorlocks, etc.), based on monitored home variables parameters (temperature, light intensity, humidity, intrusion, etc.). The user can control the equipment connected to the HA system by using a smartphone, a tablet or a personal computer, locally or through the Internet.

Energy efficiency management is a more recent add-on to Home Automation systems. It permits to reduce end-users costs. Reduction of costs can be attained by optimize consumption and by using periods of lower electricity tariffs. For example, to optimize consumption, lights turn on if sensor detects the presence of a person in a room, and switches off when the person leaves the room, or light switch on/off is based on the sun light sensed by a sensor. Reduction of costs by using lower tariffs means for instance to turn on for instance a washing machine, only when electricity cost is low. Lower tariffs is how DSO offer incentives to customers to reduce electricity consumption during peak periods. Peak consumption is reduced (peak shaving) because the consumption (demand) is more uniformly distributed along the day.

Home Energy Management (HEM) systems already exists on the market, however the information about the real-time price of electricity is used just to inform the homeowner. In general, the dynamic information about tariffs is provided through a smart meter installed by the Distribution System Operator (DSO). The energy management system, being aware of the electricity price and considering preferences and priorities specified by the homeowner, controls the electricity usage, by scheduling the use of home electrical appliances during the day.

In a HAN/HEM system, the main controller, the electrical appliances, the sensors and the smart meter must exchange information. Wired or wireless technologies can support the communications. Power Line Communication (PLC), that uses the electric wiring to communicate, and short wireless technologies, such as Wi-Fi, Bluetooth, ZigBee and Z-Wave are good candidates because they avoid new cables. Bluetooth Low Energy (BLE), an upgrade of Bluetooth classic, designed to reduce power consumption is the technology was initially proposed for this work. A comparison of the short-range wireless technology permitted to evaluate if the BLE is a good alternative, due to its low power consumption, low cost and its general availability in tablets and smartphones, which can be easily used to control and monitor the all system.

The general objective of this thesis work is to specify a HAN system, with energy management capabilities (HEM) where appliances, sensors and other equipment is connected using BLE technology. The specific objectives are:

- To study the BLE technology comparing its advantages and disadvantages over other short-range wireless technologies for HAN systems.
- To specify the architecture of a HEM system based on analysis of requirements.
- To select the hardware platform to develop a prototype/demonstrator.
- To select some the minimum hardware permitting to implement the demonstrator.
- To develop the firmware, the application software and the user interface.

After this introduction, the second chapter presents concepts related to Home Automation, Energy Management, Smart Grid and Internet of Things, and describes some commercially and under development HAN/HEM systems. Chapter 3 briefly
analyses and compares existent short-range wireless technologies, such as Wi-Fi, ZigBee, Classic Bluetooth and Z-wave, presented in more detail BLE. Chapter 4 proposes an architecture for a HEM system, and describes the implemented prototype. Chapter 5 describes the tests and presents the obtained results. Finally, last chapter presents some conclusions and suggests future work.

II. HOME AUTOMATION AND HOME ENERGY MANAGEMENT

This chapter describes HA/HEM systems and present a research work under developing that motivates this report.

1) Home Automation / Energy Management architecture
Both architecture’ systems include one main controller, sensors, actuators, home appliances and a platform to support connections (wired or wireless). The HEM system also include an AMI, in order to manage energy consumption. The main controller collects data from sensors and it controls actuators and home appliances. It has a processing and memory units to, autonomously, respond faces to environmental changes, responding to homeowners preferences.

To exchange information, all included devices in HA/HEM systems connect to a home area network (HAN). This network provides a path (physical or over-the-air) to information achieve the destination. Homeowner can access HAN through a smartphone, table or laptop, and directly controls electrical appliances and monitors environmental values.

2) Research
The authors of [2] develop an algorithm for a Home Energy Management scheduler to reduce the cost of energy consumption, using real-time pricing of electricity, provided by an advanced metering infrastructure (AMI). The algorithm receives the real-time electricity monitoring, appliance’s data and stochastic scheduling, and provide decisions about the state of appliances. The stochastic scheduling is important due to uncertainties in electricity price variation, appliance operation, user behaviour and preferences. The stochastic scheduling use a Markov decision process to minimize cost of energy consumption by predicting the appropriate curtailment of appliances based on the stochastic behaviour of cost of consumption. Then, Home Energy Management scheduler computes an optimal policy using stochastic dynamic programming to select a set of appliances to control. Finally, the algorithm produces outputs, based on HEM scheduler, that control selected home appliances.

This autonomous HEM scheduler is only available when the price of electricity is dynamic and changes with variations of energy consumption. Besides, simulation results validate the proposed method for HEM scheduler.

These results proof that is possible to perform an autonomous energy management to reduce consumption during the peak loads.

III. BLUETOOTH LOW ENERGY

Wireless technology seems to be a good solution to support communications in Home Automation systems and it is easier to install than wired technology. Besides, wired PLC technology is a discarded option because it causes a lot of interference. PLC cause interference with appliances that use Radio Frequency (RF) like audio receivers, wireless mobiles, etc. In Home Automation, the controller is usually not far away from the controlled devices. Therefore, Wi-Fi, ZigBee, Z-Wave and Bluetooth technologies are possible solutions to use. This chapter presents a comparison between wireless technologies and introduce the BLE technology. This work aims to study Bluetooth Low Energy. However, other wireless technologies can support communications. Firstly, is present an analysis of Wi-Fi [3], ZigBee [4], Z-Wave [5] and Bluetooth classic [6]. Afterwards, a full description of how Bluetooth technology works is present in order to understand it and compare it with a new version of his, Bluetooth Low Energy [7].

1) Wireless Technologies
Several Wireless technologies exist that can be used to connect devices that want to control. Table III.1 presents these technologies and their main characteristics.

<table>
<thead>
<tr>
<th>Table III.1 - Comparison of wireless technologies.</th>
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<tbody>
<tr>
<td><strong>Promoter</strong></td>
</tr>
<tr>
<td><strong>Standard</strong></td>
</tr>
<tr>
<td><strong>Network topology</strong></td>
</tr>
<tr>
<td><strong>Nodes</strong></td>
</tr>
<tr>
<td><strong>Frequency band</strong></td>
</tr>
<tr>
<td><strong>Data Rate</strong></td>
</tr>
<tr>
<td><strong>Data Protection</strong></td>
</tr>
<tr>
<td><strong>Range [m]</strong></td>
</tr>
<tr>
<td><strong>Power</strong></td>
</tr>
</tbody>
</table>

*Bluetooth support eight nodes per Piconet. However, connecting multiple Piconets, creating Scatternets, the number of nodes is unlimited.

As Table III.1 shows, there is not a better wireless technology. Choosing the technology to support communications depends the target application.

2) Bluetooth Low Energy
Bluetooth technology is a wireless communication technology that is simple, secure and low power. A combination of software and hardware allows transferring data between devices, since they are close. Bluetooth technology is able to paring one Master device with no more than seven Slave devices, performing a Piconet network. However, Slave devices can connect with more than one Master device, creating overlapping Piconets that performs Scatternets. Scatternets allows an unlimited number of interconnect devices because devices from different Piconets exchange data, since there is a path between them, created by intermediate devices.
There is the concept of Central/Peripheral, which refers to establish a connection, also known as GAP role. A Peripheral advertises to inform the Centrals that it is available to start a connection, although it is only a Central that can actually send a connection request to establish a connection (pairing). When pairing occurs, the Central is Master and the Peripheral is Slave. There also is a concept of Client/Server, also known as GATT role. The GATT Client is the device that accesses data on the remote GATT Server via read, write, notify, or indicate operations, while GATT Server is a device that stores data locally and provides data access methods to a remote GATT Client. One Master can support until seven Slave connections, at a time, creating Piconets. Slaves can connected with two Masters, alternately, linking two Piconets, creating Scatternets. There is no limit for the number of Scatternets.

Load controller is responsible to collect data from sensors, including current consumption of variable appliances, and/or to control the respective electrical appliance, based on control signals sent by main controller. Load controller sends to main controller the data collected and responses to control signals. The smart meter receives a message from DSO, containing the real-time price of electricity or requests for decreasing the consumption, and sends to main controller. The main that adjusts the schedule of variable loads, based on priorities defined by the homeowner.

Architecture described in Figure IV.1 extends the HEM system control to the outside world. It includes a Wi-Fi connection to the home router, which makes the HEM unit addressable, through an IP address. Wi-Fi is obviously more convenient than wired Ethernet cables, mainly because the mobility. The proposed system also allows to homeowner interact directly with main controller, through a BLE App, running on smartphone. To cover an entire house, each room includes a local controller, creating Scatternets.

2) Prototype Implementation

This section describes the Hardware and Software developed, as well as BLE protocol used. The prototype architecture bases on HEM architecture proposed, but does not include Energy Management. The connection to router is also change to Ethernet, for simplicity. Prototype implements a continuous connection between main controllers and load controllers to increase the transmission performance, decreasing transmission latency. The prototype simulates an environmental controlling system and an alarm system. The main controller can act by itself, actuating over electrical home appliance autonomously.

A. BLE Protocol

BLE supports communications inside the house. According to III.2), the main controller access to data available on load controllers and load controllers responds to main controller requests, then the main controller links to a Central device and each load controllers link to one BLE Peripheral device.

B. Hardware

The prototype needs a main controller, three load controllers, three BLE devices, acting as Peripherals, one BLE device architecture, collect current consumption of variable appliances and it actuates over electrical appliances.

IV. PROPOSED HEM SYSTEM

This chapter presents the proposed HEM system, describing system’s architecture and the implemented prototype, describing used Hardware and Software. The proposed system is a solution for Home Automation with Energy Management, where BLE supports the communications inside the house.

1) Architecture

The architecture of proposed HEM system, presented on Figure IV.1, have a main controller, which supports BLE communication, sensors, router, Smart Meter and two types of electrical appliances classified as critical and variable appliances. This proposal assumes that electrical appliances and sensors includes an internal load controller, with BLE support, to communicate with main controller. The Variable appliances are the appliances that do not have a fixed period of the day when they have to work, such as water heater, air-conditioning, etc.

The main controller collect data from sensors, collect current consumption of entire house, which it is not present on...
acting as Central, tow sensors and one electrical appliance. Specific hardware choose is an Arduino Ethernet, tow Arduinos Uno, two BLE Shields v2.1 (Peripheral), two Core51822 (one Peripheral and One central), the DHT11 sensor and one Smart Plug, as Figure IV.2 shows. The Smart Plug is a remote electrical socket that worked with 433MHz RF technology and it is modified to work with BLE technology. Controlling a Smart Plug, provides to control any electrical appliance that links to Smart Plug. The Core51822 includes a microcontroller that can work as load controller.

Arduino Uno with BLE Shield performed load controllers, since they join the BLE support with a process unit.

C. Software

The software includes Arduino’s boards programming, BLE modules programming, webserver development and BLE App configuration. To program Software it is used some Software tools. The list above presents the Software tools to design this prototype:

- Arduino IDE.
- Keil MDK-ARM.
- Nordic SDK.
- nRFgo Studio.
- Evothings Studio.
- Apache Cordova.

It was developed software to program Arduino’s Ethernet and Uno boards, Arduino BLE shield, Core51822 modules, as Central and Peripheral, webserver and to configure the BLE App.

Figure IV.3 presents the flowchart that represents the code uploaded to Arduino Ethernet. As Figure IV.3 shows, the Arduino is responsible to develop HTML code to send to a webserver that decodes it and presents a user interface, as Figure IV.4 shows. Through web user interface, the homeowner can control and monitor his home system.

The developed code to program Arduino Uno with BLE shield was create BLE stack to be compatible with Central device, read data from UART, read data from BLE and send data to Central device through BLE. The developed code to program the Core51822 as central device needs to:

- Start Scanning if connected devices are less than 7.
- Enable UART.
- Discover Peripheral devices that are advertising.
- Connect to peripherals if service UUID matches.
- Discover services.
- Enable CCCD if characteristics UUID matches.
- Send read and write requests to a characteristic value of a peripheral’s service.
- Execute commands from UART.
- Send notifications to main controller, through UART.

![Figure IV.2 - Adapted Smart Plug with Core51822.](image)

![Figure IV.3- Representation of program running on Arduino Ethernet.](image)
The developed code to program the Core51822 as peripheral device needs to:
- Create one service with two characteristics.
- Start advertising and wait for connection requests.
- Connects when receive a connection request.
- Respond to read and write requests from a connected central.
- Enter in low power mode.

![Smart Home Interface](image)

**Figure IV.4** - Web user interface when BLE peripheral devices are disconnected.

The App provided by Evothings Studio already has a BLE stack implemented. It was configured to establish a connection with one BLE device and send 1 byte when the user press a button on app interface. To include the App on this prototype, it needs to adapt BLE protocol to can establish a connection with Peripheral devices. It also needs to change the interface to allow the user selects the Peripheral that he wants to connect and select the order to control the electrical appliance or monitor the sensor. The data packets exchange are the same with BLE central device. Actually, BLE android APP actuate like a BLE Central device. Figure IV.5 represents the Arduino Ethernet linked to Core51822 and to router through Ethernet connection. Figure IV.6 represents the BLE App interface. Figure IV.7 represents the full architecture of the prototype. The Smartphones and tablets, on this implementation, access the system through internet. The App only works when the main controller is turned off. In this case, the App can control and monitor directly the DHT11 sensor and the Smart Plug.

![ BLE Controlling Electrical Devices](image)

**Figure IV.5** - Arduino Ethernet linked to Core51822 and to home router.

**Figure IV.6** - BLE App interface, without any connection.

![HA System Prototype](image)

**Figure IV.7** - HA System Prototype.
V. TESTS AND RESULTS

This chapter presents functional results and experimental results about the current consumption in different BLE modes (scanning, advertising, idle and standby), BLE range and transmission latency in the developed prototype. Functional tests intends to study the Home Automation system behaviour. The results shows that the system works as expected, responding correctly for all tested actions. These tests simulates an Home Automation system, where user can control and monitor his system through an web user interface or through a BLE App, running on Smartphone.

Latency tests intends to measure how much time one action takes to achieve the action target. The results, which are an average of 2 second for system response to an action, satisfied the requirements, considering home automation.

Range testes intends to measure the real range of BLE modules, the Core51822 and BLE shield, inside the house and in open space. The results are on Table V.1. Compared to BLE range described on Table III.1, the open space range is higher than expected. The range inside the house decreases a lot with obstacles. Considering Home Automation, this range is short to the purpose of Home Automation.

<table>
<thead>
<tr>
<th>Chip</th>
<th>Environment</th>
<th>Range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>nRF51822</td>
<td>Open Space</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>Inside house</td>
<td>13</td>
</tr>
<tr>
<td>nRF8001</td>
<td>Open Space</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Inside house</td>
<td>11</td>
</tr>
</tbody>
</table>

To measure current consumption, the Core51822, acting as Peripheral, is tested in four modes of BLE communication, advertising, pairing, standby and sleep modes. Table V.2 presents the experimental results of current consumption tests.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Average Current consumption [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advertising</td>
<td>1.2</td>
</tr>
<tr>
<td>Pairing</td>
<td>2.82</td>
</tr>
<tr>
<td>Standby</td>
<td>0.22</td>
</tr>
<tr>
<td>Sleep</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The results shows that Core51822 is a low-power microcontroller and that the standby mode is more power efficient than advertising. Considering Home Automation, where the system requires a faster answer between Central and Peripheral, it is more efficient if they are always connected, instead of Central request a connection every time it needs. Sleep mode is very power efficient. However, there are only two ways of the chip wake-up. One is by a physical contact, which does not satisfy the requirements because it removes the autonomous function of the system. Another way is to define an interval for the chip wake-up. If this interval is small, the consumption is higher than in a standby mode because the device has to advertise and pair. And if the interval is large, the system response will be less efficient.

VI. CONCLUSIONS

This work achieves the proposed objectives, such as the implementation of a BLE communication between a smartphone, a tablet or a personal computer with home electrical appliances, as well as design an architecture of a Home Automation system with energy management (HEM). These two main objectives permit to create a demonstrative system of the proposed architecture. This prototype permit to perform a full analysis of BLE technology. However, to simulate a larger Home Automation system it needs some improvements.

The requirements influence the architecture. The main requirement is to control and monitor electrical home appliances and sensors, from everywhere. To achieve it, the main controller communicates with these devices through BLE, inside the house, and it has an internet connection to provide the homeowner the full access to his home system from everywhere. To achieve HEM, the main controller communicates with smart meter to perform a smart energy management.

The developed prototype was created to demonstrate a Home Automation system, without energy management, where BLE support the communications inside house, and the homeowner controls and monitors his home system through internet. A prototype with three Arduino boards, two BLE shield, two BLE modules, two sensors and one smart plug allows testing a demonstration of using BLE in Home Automation, which matches with Home Automation requirements proposed. Software was develop to program the Arduinos, Shields and BLE modules to accomplish the requirements. Prototype was successfully build. However, some details can improve system performance, price and mobility. Ethernet communication decrease the Main Controller mobility. Arduinos as load controllers are too large, too expensive and consumes a lot of current considering their purpose. On user interface on Web, the status confuses the user. This parameter must refer only to the BLE connection status and the appliance or system status should be present on another place. About BLE App, it is outdated, because it is not allow the automatic mode and does not communicate with Alarm system.

About future work, there are some changes to increase the system value to homeowners and to decrease the costs. The first, which is the most important, is replace the main controller to another with more available memory to programming. Raspberry pi could be a solution because it is a microprocessor, which is much faster than Arduino and provide 512 MB of memory. Raspberry pi also include an Ethernet interface. Although, the HTLM page occupies about 34% of dynamic memory available of Arduino Ethernet. If the cloud allocates code to program HTML page (normally paid)
instead of Arduino Ethernet creates HTML page, Arduino Ethernet offers more memory for programming. The security is also an improvement to perform. Security on alarm system, on web user interface and on BLE communication. To achieve an HEM system, the HA system needs to include a smart meter to implement the communication with DSO to receive information about power consumption and real-time electricity price. It is also necessary to implement scheduling algorithms, based on homeowner’s settings and preferences, which reduce the power consumption during the periods of peak loads. Experimental tests permitted a deeper analysis of BLE technology, namely testing current consumption with different values of TX power, with different values for advertising interval, connection interval, and so one. Concluding, the results of this work shows that BLE can support communications inside house, due to its limits, like the small range. However, the compatibility with smartphones and tables is a great advantage in this area. The low-cost and low power consumption increase a lot the potential of this technology.

REFERENCES