# ZBeeMeR
# A ZigBee Automatic Meter Reading System

André Glória
Instituto Superior Técnico
Inesc-ID / IST / UTL Lisboa
Lisbon, Portugal
Email: admg@ist.utl.pt

Helena Sarmento
Instituto Superior Técnico
Inesc-ID / IST / UTL Lisboa
Lisbon, Portugal
Email: helena.sarmento@inesc-id.pt

***Abstract*—The electric grid needs to provide utilities with a better control over power demand, while making customers aware of their energy consumption profiles. Advanced Meter Infrastructure (AMI) aims to solve this problem.**

**This paper proposes a ZigBee solution to AMI. It also presents the hardware and software developed to implement it. The proposed AMI system is supported by a ZigBee mesh network where energy meters are the nodes. A unique concentrator enables the communication between the meters and the utility. It aggregates metering data and requests from the utility.**

**The developed hardware connects to the energy meter by an RS-232 interface, enabling it to communicate through ZigBee. Developed software supports the hardware and the metering infrastructure. Code running in the Energy Meter Sensor Nodes (EMSeNs) enables autonomous and periodic report of energy measurements, handles communication with the meter and responds to requests. Access to the metering information and interaction with the Wireless Sensor Network (WSN) can be done through the developed web interface, that runs on a server.**

## I. Introduction

Today's electric grids are outdated. The traditional manual energy meter reading wastes, time and manpower. Its unreliability and low frequency of occurrence produces data that is both, useless for energy production/distribution real-time decisions and for accurate consumption measurements and billing. A better control over the energy production, distribution and consumption is required.

Wireless technologies for short and medium range communications already cover many applications, such as consumer electronics, building control, industrial process control and home automation. ZigBee plays a significant role among these technologies.

In the last years, ZigBee and IEEE 802.15.4 have proved they can achieve good results for low bit rate applications, in the same way WI-FI did for high bit rate wireless Local Area Networks (LANs). ZigBee is a specification that extends the Physical (PHY) and Medium Access (MAC) layers defined by the IEEE 802.15.4 protocol, providing network features like, hierarchical/stochastic addressing, route discovery, packet forwarding, authentication and encryption. There has been a fast growth of ZigBee as a de facto standard for WSN. Large reliable deployments, using ZigBee, are now in place implementing ad-hoc WSN, such as, AMI in Goteborg [1], room locks in Mandalay Bay Hotels [2] and the equipment tracking at Tri-City Medical Center [3].

Advanced Meter Infrastructure (AMI) and Automatic Meter Reading (AMR) are examples of applications for IEEE 802.15.4 and ZigBee WSN. AMI refers to a metering infrastructure that records and reports customer consumption, hourly or even more frequently in a day. It allows customers to make real-time choices about power utilisation and utilities to be able to mitigate demand load during peak times [4] [5]. AMI creates a two-way network between smart meters and utility business systems. In-home energy displays, thermostats, light switches and load controllers are already a reality [6]. Utilities also benefit from this two-way networking since it improves reliability, and allows for dynamic billing and appliances control.

ZigBee Alliance specified in 2008 the Smart Energy (SE) profile to help the implementation of AMI over a ZigBee WSN. The SE profile specifies device descriptions and standard practices for demand response, load control, pricing and metering applications. Its purpose is to allow interoperability among ZigBee products produced by various manufacturers. In March of 2009, ZigBee Alliance stated [7] it would incorporate global IT standards from the Internet Engineering Task Force (IETF) into the SE profile, to provide applications with native IP support. More recently, they announced [8] a collaboration with Wi-Fi Alliance, to use 6LoWPAN in the SE profile. 6LoWPAN is a compression mechanism that enables the use of IPv6 in IEEE 802.15.4 based networks.

Other AMI/AMR implementations have been reported. In [9] they propose a dedicated router infrastructure for message handling to which the energy sensors then connect. They also employ a load balancing scheme, by simultaneously using more than one channel to send data, because, in their solution, any costumer interaction must go through the network concentrator. In our solution, such interaction can be provided directly by the EMSeN, freeing the network from unnecessary traffic. We also consider it redundant to use a dedicated router infrastructure. Our network infrastructure is made of only EMSeNs, with router capabilities, which lowers its cost.

AMI using WSNs is the starting point for the work described in this paper. The paper proposes an architecture and describes the hardware and software developed for an

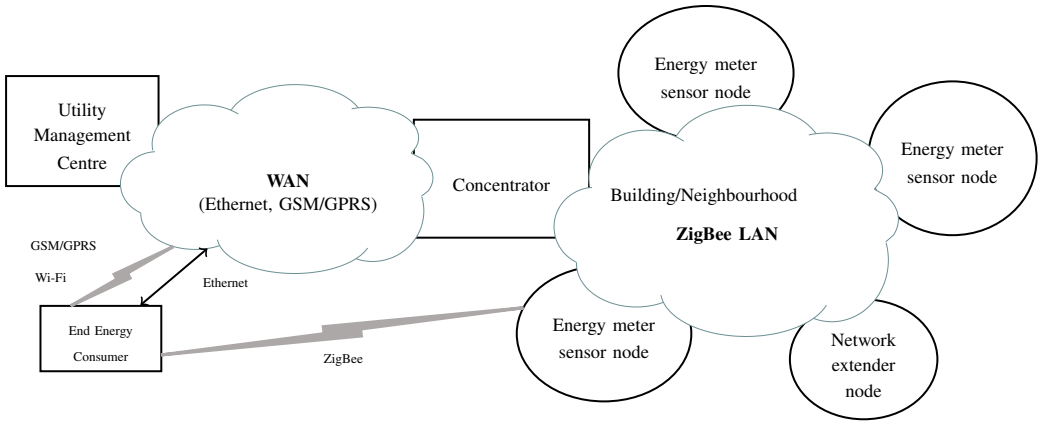


Fig. 1. Advanced Meter Infrastructure (AMI) based on a ZigBee mesh network.

AMI to be used in a building or neighbourhood, using a Zigbee mesh network. The implemented system prototype, interfaces with existing digital energy meters enabling them to communicate through ZigBee. Using Device Language Message Specification (DLMS), it can not only retrieve voltage/current/power measurements from the energy meter but it can also configure it. The structure of this paper is as follows. Section II introduces the architecture of the proposed AMI system, its components and the communication network. Section III describes hardware and software implementation details, as well as, their architecture and design. Then, in Section IV, the prototype and tests are discussed. Finally, the paper is concluded in Section V.

## II. System Architecture

ZBeeMeR is an AMR system that provides a cost effective way to upgrade an existing metering system. It regularly transmits energy consumption to the utility and can also enable consumers to monitor their consumption far more accurately, on a daily basis.

The proposed architecture (Figure 1) addresses a building or neighbourhood, creating a ZigBee WSN in which the energy meters are the network nodes. The communication between, each node and the utility management centre, over a Wide Area Network (WAN), is assured by a special node, the concentrator. The energy meters do not require a direct connection to the utility management centre. For the WAN we can use Ethernet [11], GSM or GPRS [12] [13] technologies.

Due to the fact that some energy meters can be out of range with the concentrator, all of them perform message routing. It can also happen that the metering nodes do not cover the building or neighbourhood. In such case, network extender nodes, without metering capabilities, can be used to provide the necessary coverage.

Figure 1 presents the most important components. Each Energy Meter Sensor Node (EMSeN) is able to autonomously and independently report metering values, according to a predefined parametrisation, and to respond to external requests. These nodes require small computational power. However, memory can be an important issue, depending on the specifications of the time interval to maintain metering measured values. Additionally, nodes need to be energy autonomous to permit to identify the source of a possible blackout. Under normal conditions, they are powered by the electric grid.

The concentrator requires significantly higher resources. It bundles together the collected data, either from EMSeNs or network extender nodes, to be sent to the utility. It also processes messages sent by the utility to the nodes, such as, software updates, test commands and configuration commands. As the concentrator has gateway functionality, it can implement access control permissions, exposing different information to different types of users.

The utility management center permanently stores metering information. It analyses this information to enable users to access it, to enable dynamic billing and to better adjust its production/distribution network to the real-time demands. It can also remotely configure and update an energy meter.

To conclude, the end energy consumer represents any in-home devices that can display metering/billing information or control appliances. Such device can get information directly from a utility WAN accessible interface, or through ZigBee from an EMSeN. This component is an add-on to the ZBeeMeR system, since it is not directly involved in the automatic energy meter reading infrastructure.

## III. Implementation

We implemented a beaconless mesh network that routes packets, according to Ad hoc On-demand Distance Vector (AODV) or tree routing if AODV fails [15]. The on demand nature of AODV enables to discover a new message path if the previous found one changes due to a node failure. Device addressing is done with an hierarchical addressing scheme that allows each device to have up to six children, and allows to form a network with a maximum depth of six hierarchical levels.

ZigBee permits the formation of beaconless mesh or beacon-based tree networks, besides the star topology [16]. Using beacons, that are synchronisation frames sent periodically, devices can save power by sleeping for some periods.

As EMSeNs are normally powered by the electric grid, we focused on having a self-healing reliable network in detriment of power consumption reduction. Additionally, a tree network relies on a static distributed hierarchical addressing scheme to route messages. If adopted, any failing node in the network would disconnect all nodes beneath him, rendering the branch useless.

The concentrator is the coordinator of the ZigBee network. Actually, any ZigBee network must have a coordinator that chooses the channel (from the available ones), sets the network ID and defines other key network parameters. As the coordinator address is always zero (0x0000), code for discovering it can be omitted from the EMSeNs, simplifying their code. All nodes (figure 1) are routers.

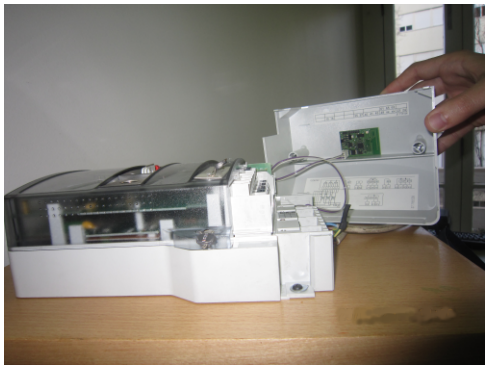

Fig. 2. The Energy Meter Sensor Node.

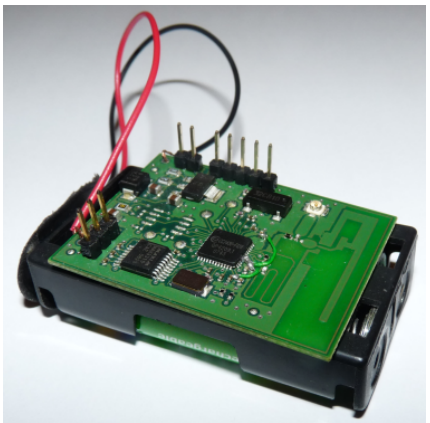

Fig. 3. The Energy Meter Sensor Node.

For prototyping purposes, EMSeNs are commercial energy meters connected by RS-232 to a ZigBee module (figure 2) and network extender nodes are accomplished with just the ZigBee module powered by rechargeable batteries (figure 3) The concentrator will be an embedded system with a WAN interface. For prototype purposes it is a PC with an ethernet card and a ZigBee interface (figure 4). The utility management centre is implemented on another PC running an Apache web server. This server is accessible over the internet, allowing for the concentrator to communicate with it. The end energy consumer device is any PC with an internet browser that connects to the Apache web server.

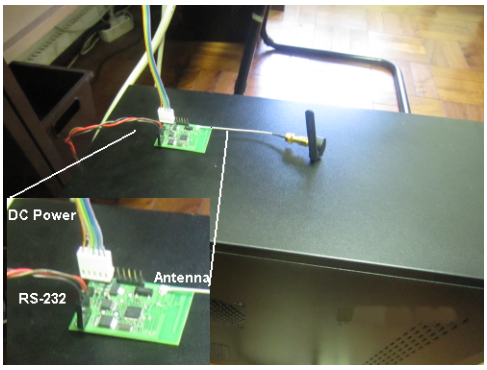


Fig. 4. The concentrator.

### A. Hardware

We decided to develop a ZigBee module instead of using a commercial one. We wanted to have a base layout design that we can control and modify, to be used in different applications with different interfaces. Figure 5 presents the module.

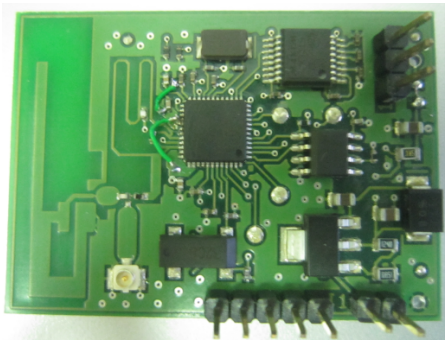

Fig. 5. The developed ZigBee Module.

We looked for ICs available on the market [17]. We choosen between Jennic and Texas Instruments (TI). The Jennic solution is more powerful, but requires an external flash. However, the choice for the TI CC2430 chip was mainly due to prior team knowledge about this platform and its development software. Besides the ZigBee System on a Chip (SoC), the module includes a RS-232/TTL converter and a voltage regulator. A Printed Circuit Board (PCB) Inverted F antenna (IFA) or an antenna connected through an U.FL connector can be used. The balun for both antennas was implemented with a few components and a transmission line trace, as suggested by TI [18].

The PCB was designed, addressing signal integrity issues for digital circuits, such as loop inductance, crosstalk and Power Distribution Network (PDN) issues. A 4-layer PCB was used, with the inner layers for ground and power distribution and the outer for signal routing and component placing. To reduce loop inductance and crosstalk, we avoided discontinuities on the planes. Also for crosstalk reduction, all empty routing

space was filled with copper, and connected to the ground plane. PDN bypass capacitors, near the ICs power pins, are used to connect them to ground plane. Traces were kept as small as possible and chamfering corners are used, to avoid transmission line reflections.

Components were arranged according to their functionality to help crosstalk mitigation between unrelated signals. Smallest component packages were used to ensure low Equivalent Series Inductance (ESL).

### B. Software

Figure 6 presents the software architecture. Major components are:

- the EMSeN that reports metering information, responds to requests, routes messages between ZBeeMeR nodes and allows new devices to join the network;
- the network extender node, which only routes messages and allows new devices to join the network;
- the concentrator that requests, aggregates and provides information from all network nodes;
- the apache web server that displays metering data and allows to send requests to the network or an individual node.

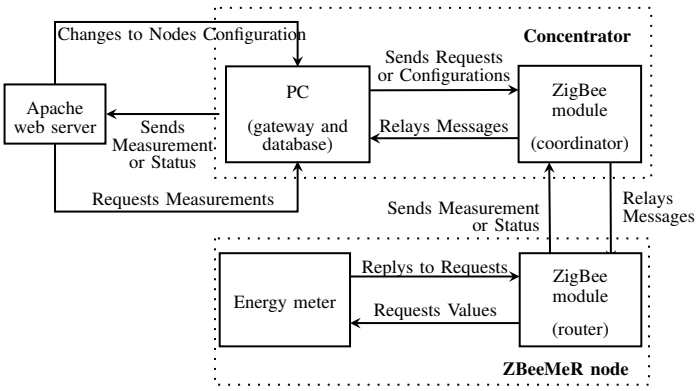


Fig. 6. The Software Architecture.

All nodes host the ZigBee stack, Z-Stack [14]. Z-Stack compile options shall be defined/optimised [15]. These options include the network ID, the frequency channel, the device logical type (coordinator, router or end device), the number of children, the use or not of encryption, and retry, time-out and delay values.

The software running in the ZigBee module of the concentrator implements the ZigBee coordinator functionality. A gateway functionality, to translate data between the ZigBee network and the WAN, is implemented on a PC. Data from the ZigBee network is translated by the coordinator into a custom serial protocol, over to the gateway and database management PC. The latter then provides the WAN access. The storage and access to the information about timestamps, measurement values and status, is C# code running in the PC. An interface to local data access was also developed in C#.

An EMSeN implements the ZigBee router profile, to allow network associations and message relaying. This node also implements the IEC 62056-21 Mode C protocol [19] for communication with the energy meter. The network extender node only implements the ZigBee router functionality. Although being different components, EMSeNs and network extender nodes run the same software. This software will perform differently according to the presence, or absence of an energy meter. EMSeNs are able to request metering data from the energy meter and send it to the concentrator while, network extender nodes are not and fall back to a ZigBee router only behaviour.

All ZigBee modules are programmed using the IAR Embedded Workbench v7.30b and coded in C programming language.

The remote PC running the apache web server, runs an application that maintains a metering data database with the periodic information sent by the concentrator. This remote PC also provides a web interface, (figure 7) mainly coded in JavaScript, to display the metering information and to allow messages to be sent to the ZigBee network. These messages are sent over the internet to the concentrator that in turn delivers it to the ZigBee network.

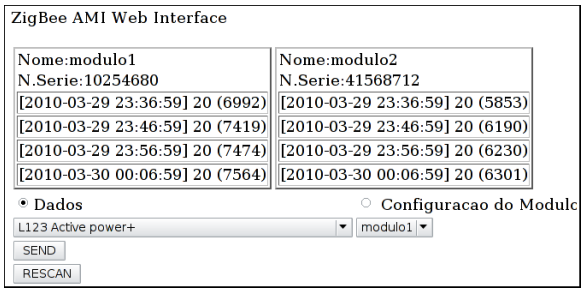


Fig. 7. Web Interface.

As can be seen on figure 7, the web interface presents information by columns. Each column represents an EMSeN, identified by the meter serial number. Each cell in a column presents the issued command, the response data and a time-stamp. The time-stamp is presented between square brackets, indicating date and time values, next the command code is displayed and parenthesis enclose the response data. Only four lines are displayed with the last commands and responses.

In the example of figure 7, columns display metering data from two EMSeNs. The interface provides two drop-down menus and two buttons. The drop-down menus allow to choose the command to be sent and its destination. The destination can be broadcast, to send the same command to to all EMSeNs or the address of a specific EMSeN. The rescan button permits to identify the available EMSeNs in the ZBeeMeR system by sending an identify broadcast request to all of them. This request requires an EMSeN to send its unique identifier together with the energy meter serial number.

## IV. Tests and Results

Several tests were performed to test the ZBeeMeR system functionality, the electrical correctness of the ZigBee module,

and the power emissions compliance with the IEEE 802.15.4 standard and ranges achieved.

### A. ZigBee Module Tests

After soldering the received manufactured PCB panel, by applying solder paste, using a stencil sheet, and manually placing components, some electrical tests were performed. These tests ensured the absence of short circuits in-between layers and chips pins, and confirmed the power levels throughout the board.

Radio emissions were verified using a Rohde & Schwarz FS300 spectrum analyser to:

1) test for the existence of emissions out of band the 2.4GHz band;
2) test for compliance with the maximum channel center frequency deviation allowed;
3) test for compliance with the maximum channel bandwidth allowed.

Due to missing equipment for measuring power emissions from the antenna implemented on the PCB, only the external whip antenna was used for the tests. However, since they use the same balun results can be extrapolated.

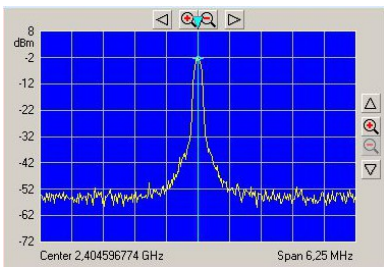


Fig. 8. Module unmodulated emission at 2425MHz.

Figure 8 shows, in detail, the testing of channel 6 emitting at 2.430GHz. The obtained value of 2.429596GHz, deviates 404Hz from the 2.430GHz. All other channels present the same deviation. As according to the IEEE 802.15.4 standard, the maximum allowed tolerance is 100Hz, further **rf!** (**rf!**) tuning is required.

Figure 9 presents the same emission over a 3GHz frequency range. Based on that, we can conclude that all frequencies are in the 2.4GHz and no spurious emissions exist.

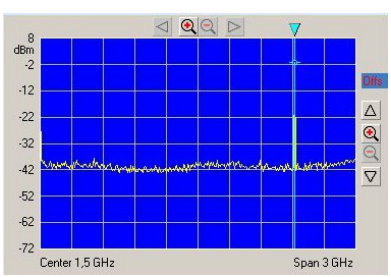


Fig. 9. Module emission at 2425MHz over a 3GHz frequency range.

Figure 10 shows the O-QPSK modulated emission on channel 6. All channels surpass the -30dBm absolute limit imposed by IEEE 802.15.4, for frequencies that verify the $|f - f_c| > 3.5$MHz condition. $f$ is the frequency in question and $f_c$ the centre channel frequency.

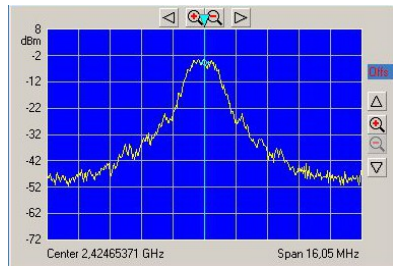


Fig. 10. Module O-QPSK modulated emission at 2425MHz.

To test for transmission ranges, several power measurements were realized. These tests include measurements from:

1) the Texas Instruments development module;
2) the developed ZigBee module using the whip antenna;
3) the developed ZigBee module using the antenna implemented on the PCB.

Each RSSI value presented, is the average of the reception of 500 packets[1] over a fixed distance of 2 meters (table I). From the obtained values, we conclude the performance of the developed module is similar to that of the Texas Instruments module. Both achieving communications below a 5 meters range, without noticeable packet loss. However, at a 5 meters range with messages of 90 bytes of payload, packet loss increases. The antenna implemented on the PCB achieves the worst range. Packet loss increases on ranges over 1 meter and is more sensitive to the payload size, than the other antenna.

We conclude that only the whip antenna and a signal amplifier should be considered for future implementations.

TABLE I
POWER MEASUREMENTS OVER A 2 METERS DISTANCE.

| Antenna Type | Average RSSI (dBm) | Lost Packets | Error (% ) |
|---|---|---|---|
| *30bytes of payload* | | | |
| Whip (TI) | -53,9 | 0 | 0 |
| | -54,9 | 1 | 0,2 |
| | -57,2 | 0 | 0 |
| Whip | -45,4 | 0 | 0 |
| | -45,9 | 0 | 0 |
| | -45,4 | 0 | 0 |
| PCB | -65,6 | 46 | 9,2 |
| | -65,2 | 85 | 17 |
| | -64,4 | 79 | 15,8 |
| *90bytes of payload* | | | |
| Whip (TI) | -57,4 | 1 | 0,2 |
| | -57,7 | 1 | 0,2 |
| | -58,2 | 1 | 0,2 |
| Whip | -45,6 | 0 | 0 |
| | -45,8 | 0 | 0 |
| | -45,2 | 0 | 0 |
| PCB | -66,2 | 95 | 19 |
| | -65,8 | 136 | 27,2 |
| | -65,8 | 130 | 26 |

[1]Packet that are loss decrease this number.

### B. AMI System

To validate the network functionality, the message routing, the possibility to increase coverage with network extender nodes, and the adequacy of ZigBee for AMI, the ZBeeMeR system was set-up. It consisted of a network with four nodes distributed on a building floor, as presented on figure 11[2]. The network includes two EMSeNs, a network extender node and the concentrator. The network extender node, situated in the corridor, assures that the data from EMSeN 1 arrives at the concentrator.

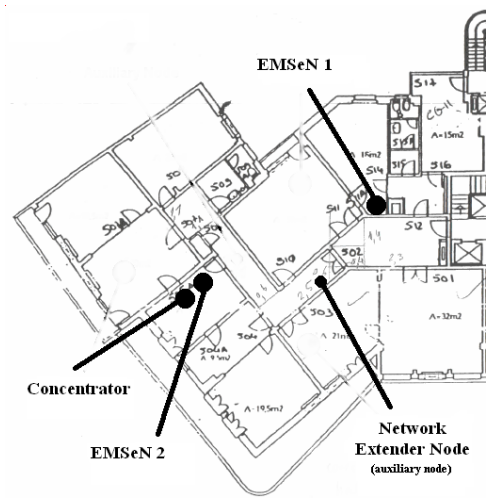


Fig. 11. Prototype network structure with nodes location.

The first three tests permit to validate the network configuration, and the last three the functionality. For testing purposes, the web interface is used to send requests and to display metering values. The metering values returned from requests sent to the EMSeN were confirmed by the energy meter LCD display.

1) Activation of the concentrator and EMSeN 1: no network association occurred because they are out of range.
2) Introduction of a network extender node: metering data from EMSeN 1 arrived at the concentrator.
3) Activation of EMSeN 2: metering data arrived at the concentrator.
4) Metering data requested to all nodes (using a broadcast message): EMSeN 1 and EMSeN 2 replied with the requested data.
5) Metering data requested only to EMSeN 2 (using a unicast message): EMSeN 2 replied.
6) Metering data, not requested, received from both EMSeNs: EMSeNs had started autonomously sending metering data at the pre-programmed periodicity.

Test 4 and 5 show that measurements can be requested to a single **empsen!** (**empsen!**) or to the whole network. It also validated the routing of messages. Test 6 demonstrates the autonomous behaviour of EMSeNs.

[2]This plant represent the third floor, right section, of the Inesc-ID building.

We can conclude that the ethernet functionality works and can give access to concentrators locally stored data. Also permitting remote measurement requests to energy meters.

## V. Conclusion

This paper proposes an architecture, describes the implementation of the required hardware, and presents the design and implementation of the software for an Advanced Meter Infrastructure (AMI). We successfully built a small low power ZigBee module that fits inside the energy meters casing, and connects to it via the RS-232 interface. The software architecture permits bi-directional communication between the meters and the utility. Metering data can be accessed from a web page.

The developed prototype allows to validate the proposed architecture and the ZBeeMeR system functionality. The simplifications made to the proposed architecture allowed for its implementation without incurring in loss of generality. The prototype allows to conclude that ZigBee is suitable to implement the bi-directional communications of an AMI/AMR system. Furthermore, installation costs are reduced by using the Energy Meter Sensor Nodes (EMSeNs) with routing capabilities, and a unique concentrator to aggregate metering data.

In addition, much can be availed in the porting of this prototype to a final system. The EMSeNs and the network extender nodes only need small improvements (further **rf!** tuning is required). The concentrator requires more rework, since in the final architecture it is an embedded system and, in the prototype, we use a PC connected to a ZigBee module. Due to the resources gap between a PC and an embedded system, the majority of the developed code has to be adapted and rewritten. For integration into an existing utility infrastructure, the communication protocols have to be analysed and implemented in the concentrator.

In a building, a power backbone vertically crossing the floors usually avoids energy meters to be scattered inside it, but rather organised according to that backbone. Therefore, the WSN can benefit from this organisation, maybe avoiding the need for network extender nodes. Further coverage related tests to test this organisation as well as to analyse the advantages and disadvantages of using a ZigBee RF signal booster also as an alternative to the network extender nodes, shall be made. Additionally, system performance tests with large networks would also be interesting to perform.

## Acknowledgment

The authors would like to thank Bithium for their support in the PCB design and assembly, and EDP - Energias de Portugal for providing the energy meters used in the prototype.

This work was partially supported by FCT (INESC-ID multi annual funding) through the PIDDAC Program funds.

## References

[1] Thomas Arnewid, *AMI in the city of Goteborg*, Metering International, pp 76 - 79, Issue 4, 2007.
[2] ZigBee Success Stories. Available, in March of 2010, from: http://www.zigbee.org/imwp/download.asp?ContentID=15272

[3] ZigBee Sucess Stories. Available, in March of 2010, from: http://www.zigbee.org/imwp/download.asp?ContentID=15796

[4] *AMR/AMI Infrastructure*, DIGI White paper. Available from: http://www.m2mpremier.com/uploadFiles/wp_amrami.pdf.

[5] *The Role of Load Research in Automated Meter Infrastructure/Meter Data*, AEIC, September 2008. Available from: http://www.aeic.org/load_research/AMI_MDMWhitePaperFinal2.pdf.

[6] Zpryme Research & Consulting, LLC, *Smart Appliances*, Smart Grid Insights, March 2010.

[7] ZigBee Alliance. (2009, April) ZigBee Alliance Plans Further Integration of Internet Protocol Standards. [Online]. Available: http://zigbee.org/imwp/idms/popups/pop_download.asp?contentID=15754

[8] ZigBee Alliance. (2010, March) ZigBee and Wi-Fi Alliances to Collaborate on Smart Grid Wireless Networking. [Online]. Available: http://zigbee.org/imwp/idms/popups/pop_download.asp?contentID=17400

[9] Hoi Yan Tung, Kim Fung Tsang, Ka Lun Lam, *ZigBee sensor network for Advanced Metering infrastructure*. International Conference on Consumer Electronics, Digest of Technical Papers, 2010, pp. 95 - 96.

[10] Kraig Mitzner, *Complete PCB Design Using OrCad Capture and Layout*, Elsevier, 2007.

[11] Liting Cao, Wei Jiang, Zhaoli Zhang, *Automatic Meter Reading System Based on Wireless Mesh Networks and SOPC Technology*. Second International Conference on Intelligent Networks and Intelligent Systems, 2009 , pp. 142 - 145.

[12] Primicanta, A.H., Nayan, M.Y., Awan, M., *Hybrid Automatic Meter Reading System*. Computer Technology and Development International Conference, 2009. Vol.2, pp. 264 - 267.

[13] Fei Ding, Guangming Song, Jianqing Li, Aiguo Song, *A ZigBee Based Mesh Network for Home Control System*. Education Technology and Training and International Workshop on Geoscience and Remote Sensing, 2008. Vol.1, pp. 774 - 748.

[14] Texas Instruments, *Z-Stack - ZigBee Protocol Stack version 1.4.3*. Available from: http://focus.ti.com/docs/toolsw/folders/print/z-stack.html

[15] Texas Instruments, *Z-Stack Developer's Guide version 1.1*. 2007.

[16] ZigBee Alliance, *ZigBee Specification*. 2008.

[17] Glória, André, "ZBeeMeR - A ZigBee Automatic Meter Reading System" Ph.D. dissertation, Instituto Superior Técnico, Lisbon, Portugal, September 2010.

[18] Audun Andersen, *DN0007 - 2.4GHz Inverted F Antenna*. Texas Instruments, 2008.

[19] IEC TC 13. *EN 62056-21, Electricity metering - Data exchange for meter reading, tariff and load control - Part21:Direct local data exchange*. CENELEC, Brussels, 2002

[20] N.Escravana, R.Lascas, M.Nunes, C.Anjos, H.Sarmento, A.Casaca, T.Silva, J.Lageira, J.Moreira, *Proposta de Arquitectura*, Technical Report, Projecto Arquitectura de Comunicações do INOVGRID, 2008.