Photovoltaic and wind energy systems monitoring and building/home energy management using ZigBee devices within a smart grid

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Received 28 April 2012; received in revised form 28 September 2012

Abstract

The actual electric grid was developed to offer electricity to the clients from centralized generation, so with large-scale distributed renewable generation there is an urgent need for a more flexible, reliable and smarter grid. The wireless technologies are becoming an important asset in the smart grid, particularly the ZigBee devices. These smart devices are gaining increased acceptance, not only for building and home automation, but also for energy management, efficiency optimization and metering services, being able to operate for long periods of time without maintenance needs. In this context, this paper provides new comprehensive field tests using open source tools with ZigBee technologies for monitoring photovoltaic and wind energy systems, and also for building and home energy management. Our experimental results demonstrate the proficiency of ZigBee devices applied in distributed renewable generation and smart metering systems.

Keywords: Photovoltaic energy; Wind energy; Monitoring; Energy management; ZigBee; Smart grid

1. Introduction

The existing electricity grid has remained unchanged for about 100 years. It lacks the capability of providing information and communication. To realise these capabilities, a new concept has emerged; the smart grid [1-4]. The smart grid is now becoming reality and the installation of smart meters, currently in progress in many countries [5], is the first step. By using smart meters [6,7], the consumption and generation profiles will be available for both consumers and grid operators. Wireless Sensor Networks (WSNs) [8,9] are becoming a fundamental tool of the smart grid. Advanced information and communication technologies [10], monitoring and control and innovative metering technologies via intelligent devices, will become increasingly important.

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The main drivers for a smarter grid are, for example: a more sustainable grid, growing integration of renewable energy systems [11,12], a higher energy demand [13] and the addition of new loads such as electric and hybrid cars [14,15]. Investment in smart grids is crucial for a low carbon electricity system, facilitating energy efficiency, distributed generation and the electrification of transport [16].

The implementation of a renewed grid must be flexible, reliable and efficient and therefore, there is a need to control its behaviour, demands, generation and transmission [17]. Sensors and actuators play an important role in this, being the "nerve cells" of the electricity grid. A robust and efficient technology is needed for the control and management of the end-to-end, bi-directional flow of electric energy in the smart grid with optimised communication capabilities.

Several technologies have been developed but one in particular is received a lot of attention; the ZigBee. This is a low power wireless networking standard designed for controlling and monitoring applications [18,19]. The ZigBee standard was prepared by an industry consortium; the ZigBee alliance. ZigBee usage in smart metering is expected to show a growth of 35% from 2009 to 2015. The US Department of Energy and the National Institute of Standards and Technology have listed the ZigBee smart energy profile as one of the most important smart grid standards. Although the expected growth of the implementation of ZigBee technology is considerable, little or no work has been done to thoroughly study and evaluate the implementation challenges in distributed renewable generation and smart metering systems.

Hence, this paper provides new comprehensive field tests using open source tools with ZigBee technologies, for monitoring photovoltaic and wind energy systems and energy management of buildings and homes. Our experimental results significantly enhance the information about these smart devices, highlighting their importance in the smart grid. This paper offers several insights into the opportunities and challenges that may be encountered in the implementation of smart devices in the smart grid. In addition, to support the reader's comprehension of the results and proposed solutions, an extra effort has been made to offer an overview of the ZigBee devices and modules and also the smart grid and metering.

This paper is organized as follows. Section 2 presents an overview of ZigBee devices and modules. Section 3 addresses the smart grid infrastructure and the importance of metering. Section 4 presents the field tests developed to evaluate the most appropriate experimental methodologies regarding ZigBee technology implementation for distributed renewable generation and smart metering systems. Finally, Section 5 outlines the conclusion.

2. ZigBee devices and modules

ZigBee is a wireless networking standard targeted at monitoring, control and building and home automation [18,19]. ZigBee is designed to interconnect autonomous sensors and actuators to control units with an emphasis on low power consumption. It is a specification based on the IEEE 802.15.4 standard [20,21], extending that definition by developing new additional higher layers.

The IEEE 802.15.4 stipulates 10 metres as the base communication range with a transfer rate of 250 kb/s but it is possible to define different communication ranges and transfer rates. It defines two different types of device: a Full Functioning Device (FFD) and Reduced Functioning Device (RFD). The FFD can communicate with any other device. It can act as sensor/actuator, it can relay messages and it can act as the personal area network (PAN) coordinator. The RFDs have few resource and communication requirements, which lowers the processing capabilities but decreases production costs. Typically, these nodes must be connected to an FFD node and cannot act as a coordinator or as a router; usually they are used as sensors. A network must have at least one FFD node that acts as a coordinator, managing the entire network. Each device has a unique 64-bit identification but can operate with a second shorter identification (16-bit) within a certain PAN.

There are three different types of ZigBee device. The ZigBee coordinator is an FFD that coordinates the network and forms its root, making a bridge with other networks, managing the network security and its security keys and also being able to store information about the network. The ZigBee router is an FFD that can have sensors and actuators but its capacity enables it to relay messages from other nodes, acting as a router. The ZigBee end device is an RFD that can be connected to sensors and actuators and can be asleep most of the time to extend the battery life. It has reduced processing capacity, which means that it is cheaper to produce but it cannot relay messages.

Taking into consideration the IEEE 802.15.4 network topologies in the ZigBee standard, in a star topology the network is controlled by one single device; the ZigBee coordinator. In mesh and tree topologies the ZigBee coordinator is responsible for starting a new network when appropriate and assigning addresses to newly associated devices but the network may be extended through the use of ZigBee routers. Several ZigBee standard application profiles have been developed, such as: smart energy, building and home automation, health care, RF4CE (consumer electronics/remote control), telecom services, monitoring and control.

The application profiles allow the normal wireless device solutions development. However, several other optimisation services can be built using the services offered by ZigBee standard layers: the synchronisation of nodes to increase data message quality [22]; the minimisation of interference on the nodes by choosing the best channels or by delivering the communication between several channels [23]; the optimisation of sleep in order to reduce energy consumption but at the same time guaranteeing data quality at optimal delivery times.

There are two main module versions in the market: ZigBee (ZigBee-2006v standard) and ZigBee PRO (ZigBee-2007v standard). The ZigBee PRO is an extended specification defined by the ZigBee alliance in 2007 and brings stochastic addressing, which in the previous specification is coordinated by the ZigBee coordinator. Table 1 provides a comparison between three commercially available ZigBee modules. Despite the XBee ZB module not having a “PRO” designation, it is compliant with the ZigBee PRO standard.

"See Table 1 at the end of the manuscript".

The ZigBee uses small, cheap, ultra-low power digital radios for the creation of low data rate wireless networks, which are secure with long battery life nodes. Therefore, these devices are suitable for sensors and network controllers that only need to exchange small amounts of data but must operate for long periods of time. Because the ZigBee technology uses little energy to operate and some of its devices can even enter into sleep mode, the energy necessary for battery or even harvesting is considerably small.

The ZigBee network should be able to connect itself with other wireless or wired networks. The ZigBee alliance offers one solution for that need, called the ZigBee gateway. The ZigBee gateway provides high feature connectivity and allows a larger diversity of applications and devices to connect and control the ZigBee networks and their devices. It translates the ZigBee network and devices protocols to a variety of other formats that exist in the industrial, commercial and residential systems, providing an interface between the ZigBee and IP devices with an abstract interface that isolates the IP device from the ZigBee protocol and translates both commands and addresses between them.

The easiest methodology of implementing a ZigBee WSN with the best return on investment is to use a wireless network that delivers the data to a ZigBee gateway device that, in turn, sends that information to a sensor cloud solution over-the-internet (Fig. 1). This sensor cloud solution can be offered by a software house or by the ZigBee modules manufacturer itself.

"See Fig. 1 at the end of the manuscript".

The devices can be controlled over-the-cloud by making a connection to the ZigBee gateway and sending a command, offering a versatile system to manage firmware updates, activity monitoring, hardware configuration and innovative services development. Having the system developed and stable, it is advisable to implement an in-house solution of a sensor cloud, which offers more control over the data exchange and eliminates the dependency on the over-the-internet solution prices and maintenance costs.

Hence, by using a cloud solution the process of implementing a ZigBee WSN and developing services for the devices are more transparent and easier to maintain and change.

3. Smart grid and metering

The ideal future grid is defined as "smart" due to the need for control by means of sensors, controllers, the use of the latest information technologies and the autonomous attributes required by numerous assets. Several definitions of smart grid exist but some of the most important definitions have been elaborated by the International Electrotechnical Commission, the National Institute of Standards and Technology, the European Technology Platform and the Institute of Electrical and Electronics Engineers. These organisations have assumed responsibility to coordinate the study and development of a regulatory framework to achieve the interoperability of all devices, systems and players of the smart grid to provide optimal performance in electricity distribution and energy quality. This framework includes standards of harmonised architecture and interoperable and interchangeable protocols.

The necessity for an upgrade of the existing grid is increasing. Some of the proposed benefits of such an upgrade are: a) accessibility and accommodation of all generation and storage options, namely large-scale distributed renewable generation; b) an infrastructure with zero or very low carbon emissions; c) economic viability providing the access to and creation of new products, services and markets; d) fulfilling the customers' needs, granting access to all information and participation in energy management; e) optimisation of grid assets and efficient grid operation with intelligent automatisms and predicted maintenance; f) improved quality of energy supply, to be reliable and capable to fulfilling future energy demands; g) efficient security against cyber and physical attacks and natural disasters; h) capability of self-healing under various system disturbances, congestion or operational errors.

Although some say the smart grid is an upgrade of the actual infrastructure and others say it is a completely new grid, we believe that it should be both. The actual assets should be optimised and their lifetime increased where possible but in an actively controlled way using the latest sensor technologies.

The future grid should grow alongside the existing grid and when necessary, should start to replace existing assets in order to reduce the installation costs and to spread the investment in the smart grid over a longer period of time, optimising resources and targeting intelligent distribution of investment to the most needed areas. The European Commission has invested €300 million in 300 smart grid projects that had an overall investment of €5.5 billion under the Seventh Framework Program.

In today's grid, the energy has only one direction of energy flow but in the near future, it must be bidirectional with an interchange, not only between regional grids but also between players, leading to the interchange of energy and information, as shown in Fig. 2.

"See Fig. 2 at the end of the manuscript".

The control of such a system must be efficient and easy to maintain and operate, albeit highly complex and secure. Therefore, in a future grid, several automatisms are required and the sensors, actuators and their data exchange with the grid players will have a crucial role. Because operators will not be able to be reactive enough to the needs and challenges of the smart grid, the assets must be "smart" enough to acquire and process the sensor data and to act upon the results in a fast and optimal way.

Several technologies will be used in the smart grid generating a large amount of information and thus, it needs to operate semi-automatically with artificial intelligence capabilities.

These smart devices will positively impact energy generation and distribution and the health and optimal operation of grid assets through: a) supervisory control and data acquisition systems; b) real-time situation awareness and analysis; c) higher control over the grid function to the operators; d) substation automation that enables utilities to plan, monitor and control equipment in a decentralised way; e) broader application of power electronics and new technologies; f) fault location and isolation to quickly recover when outages occur; g) implementation of smart meters to allow customers to increase their control of energy usage and costs; h) implementation of energy management systems that will optimise energy consumption.

Meters will play a very important role in the connection between consumers and the grid, not only offering real-time energy usage information to the grid but also in bringing real-time information from the grid to the consumer, acting as a bidirectional information gateway. The actual home must be an intelligent environment with smart appliances that can respond to grid fluctuations and peak demands with sensors that continually control their energy use and intelligently adapt their behaviour to a convenient profile, not only for the grid but also, especially for the customer.

As it can be seen in Fig. 3, not all European countries evolve at the same pace. Europe is a heterogeneous region with countries that have very different needs and visions of the smart grid and therefore, the European role in the regulation and development engines is of fundamental importance.

"See Fig. 3 at the end of the manuscript".

Smart metering systems are expected to provide, not only an adequate billing system with cheaper energy for the consumer but also benefits to the grid, providing the ability to function with fewer operational errors due to a more adequate management of assets and energy demands.

4. Field tests and evaluations

The field tests conducted with the ZigBee devices are intended to carefully evaluate their ability to create the network mesh, the self-healing characteristics, the security issues and the installation and position of the devices, always taking into consideration the needs and concerns of each distributed renewable generation and smart metering system. Additionally, there is a premise to create and use open source, low-cost and easy-to-operate hardware kits. A schematic of the ZigBee coordinator is presented in Fig. 4.

"See Fig. 4 at the end of the manuscript".

The ZigBee modules selected were the XBee ZB, which are low-cost, low power devices able to implement the ZigBee PRO standard. It was considered that the ZigBee coordinator, routers and end-points should all be autonomous devices with their own energy supply. Additionally, all the systems were built with breadboards, so that the hardware components could be easily changed on-site, if necessary. To control and manage the data received by the ZigBee coordinator, the open source Arduino Uno board was used. This board was programmed to collect and process the data received from the connected ZigBee coordinator connected, showing these data on an LCD display. The ZigBee coordinator device that was experimentally built is shown in Fig. 5.

"See Fig. 5 at the end of the manuscript".

The base configuration for the field tests had one coordinator, one sensor that would be used to test a certain position/installation and a set of routers that would only be used if interference in the message delivery was detected. Three devices were created and used as routers and sensors. These three devices had the same configuration and could be used either with or without connected sensors or actuators. The devices without sensors or actuators act only as routers that simply relay messages.

All the ZigBee devices were configured with two LEDs that indicated when the ZigBee had power (red light) and when it belonged to a WSN (yellow light). In the ZigBee coordinator, the yellow light is constantly on because it creates and manages the WSN, whereas the yellow light blinks for the other ZigBee devices.

The cluster-tree topology was used in the field tests because it is the best solution for WSNs with a high number of nodes. This type of network requires less energy and has a faster message transmission time but may imply a slightly higher self-healing time.

Nevertheless, in our experimental results the self-healing process took only about two seconds, which is acceptable and in a network with fixed position installation devices this healing time is negligible, as it will only be used in extreme situations. Only when the ZigBee devices are in constant movement must this self-healing time be taken into account and in such a case, the mesh topology should probably be considered with some sacrifice of the message transmission time.

The same batteries were used in all the field tests and they are still in full use. The highest energy consumption is for the Arduino board. The experimental results presented represent a variety of different situations where the ZigBee devices would be used in a smart grid environment for monitoring photovoltaic and wind energy systems and also for building and home energy management. In addition, the challenges encountered and the solutions and installation approaches are presented.

4.1 Photovoltaic energy system monitoring

The photovoltaic energy system (Fig. 6) considered in our field tests belongs to the operator of a water treatment and distribution system (SMAS). Enabling the monitoring system to be capable of communicating through a wireless medium [24] will certainly give flexibility to the technicians. The company has several water reservoirs each one with 18 solar tracking photovoltaic panels installed. Each photovoltaic panel has a rated power of 220 W, 60 cells, maximum voltage of 29.3 V and a maximum current of 7.51 A.

"See Fig. 6 at the end of the manuscript".

The inverter used for the grid connection is presented in Fig. 7. All the electricity generated is injected into the grid and is not for internal use; this adheres to governmental regulation (DL No. 363/2007), which stipulates all the electricity must be fed into the grid.

"See Fig. 7 at the end of the manuscript".

Fig. 8 shows the inside of the water supply installation with the ZigBee coordinator suitably placed. The real-time data can be sent directly to a web service via an internet connection and can be monitored via a web portal service.

"See Fig. 8 at the end of the manuscript".

Several parameters require monitoring, namely: photovoltaic cell temperature; power quality of each panel; inverter functionality parameters; solar tracking system position; solar intensity and position. Other aspects related to the operation must be taken in consideration when installing controllers to operate remotely the solar tracking system, or to connect/disconnect the entire system or part of it.

A distance test evaluated the possible interference of several components when a ZigBee device was installed: photovoltaic panel; tower; inverter and metallic structures. No significant interference was detected with all messages delivered to the coordinator.

Other experiments were performed on the components of the water supply installation: reservoir; machine house and water pumps. In a distance test with a maximum of 50 m (the size of the testing site) and without the use of routers, no interference was detected, except when the water reservoir was in the transmission path. This interference was easily overcome via triangulation with the help of a router. The machine house installation has one level below ground and one level above surface, which follows the water tank height. By placing the ZigBee coordinator at the lowest level, no interference was detected, except when the water tank was in front of the transmission line. Again, with the help of just one router the interference was overcome.

In this installation, it is advisable to use a maximum of one router to transmit the signal and only if the water tank is in the line-of-sight. The use of a ZigBee device just to route messages is not a desirable optimisation of resources and therefore, it is recommended instead to use some of the sensors distributed within the site with routing capabilities. The sensors that could perform this task could be: the water level sensor; the water tank temperature sensor; or the sensors at the entrance to the site or machine house.

A beacon-enabled network with start topology could be used, taking advantage of the sleeping mode of several sensors to reduce energy needs even further. Nevertheless, several sensors must be active all the time but some, such as the water level or solar radiance sensors can remain asleep most of the time. In this case, it is advisable to position the coordinator at the top of the water tank.

4.2 Wind energy system monitoring

The wind farm considered in our field tests has over fifty wind turbines (Fig. 9). Fig. 10 shows the lower part of the tower of wind turbine GA 29.

"See Fig. 9 at the end of the manuscript".

"See Fig. 10 at the end of the manuscript".

Several tests were made inside the control house of the wind farm (Fig. 11), which has a constant voltage of 30 kV passing through the break switch. No interference was detected even when the ZigBee coordinator and the sensors had equipment in their line-of-sight. Therefore, the use of routers was not necessary

"See Fig. 11 at the end of the manuscript".

Substantial interference was detected when the signal was transmitted with the reinforced metal door of the control house in the transmission path. This interference was overcome by placing a router in the wall beside the reinforced door. The substation (Fig. 12) also produces a considerable level of interference, which affects the signal strength as occurred in [25]. Even with standard communication cables, the interference was detected because of the 150 kV/30 kV in the substation.

"See Fig. 12 at the end of the manuscript".

Other tests were made with the line-of-sight range that were compliant with the technical specifications of the devices (120 m with no obstruction), except when the devices where placed near the substation. In this situation, the use of one router was sufficient to overcome the interference. No interference was detected from the power lines that were placed underground.

The installation of ZigBee devices inside the tower of a wind turbine (Fig. 13) and near the electric components did not suffer from any interference, and therefore, it can be considered that the ZigBee devices can be used effectively to create a WSN to monitor the wind turbines without restrictions

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It should be noted that the ZigBee devices used in the field tests were the least expensive (and without more advanced characteristics) in the market. Even so, these smart devices proved to be fully capable for use in a wind farm. Although the devices used in the field tests have proven to have sufficient capability to monitor the wind energy system with no restrictions, to create a WSN between the wind turbines and the control centre, it is advisable to use devices with higher transmission power.

4.3 Building energy management

Metering is a fundamental part of a smart grid infrastructure. The field tests to evaluate the ZigBee devices installation were conducted in a complex of buildings with eleven floors. The ZigBee devices placed in the gas, water and electricity meters (Fig. 14), electricity boards and gas installations (Fig. 15) were thoroughly tested for interference. Several obstacle types were tested, such as the main structural reinforced walls that are usually wider than normal, fireproof doors, reinforced house doors, elevators, and several others.

"See Fig. 14 at the end of the manuscript".

"See Fig. 15 at the end of the manuscript".

No interference was found despite the indoor range (of 40 m) over which the ZigBee devices were tested. Even the direct messages broadcast between the sensor and the coordinator over several floors had very positive results. The sensors could remain in sleep mode most of the time and occasionally broadcast their monitoring data, in order to reduce their energy use as much as possible. For the electricity meters, a period of fifteen minutes between broadcasts is usually sufficient. For the gas and water meters, one broadcast of data every day would be sufficient. Larger sleep mode periods are also possible. In this situation, the meters could have sufficient energy for several years of operation. Additionally, the sensors could have their own micro energy harvesting.

To be able to put the devices in sleep mode, the WSN needs to have permanently active routers or sensors directly connected to the coordinator in the star topology. A beacon-enabled mesh network with the meters sensors routing the messages could be used but because they are in sleep mode, the synchronisation and delivery of the messages is more difficult and complex, which may lead to an undesirable cost increase. It is also possible to have one coordinator per building gathering the meters' data and sending them to the utilities services over other network technologies, such as fibre optic, phone lines, or GPRS. Another solution is to have a router in each building relaying the meters' data to the ZigBee coordinator, which can be installed per street, or even one coordinator installed in the utility facilities. The routers installed in each building would create a network mesh that can cover a very large area, with up to 65000 nodes.

4.4 Home energy management

Several field trials were also conducted in an urban home, whose configuration is shown in Fig. 16.

"See Fig. 16 at the end of the manuscript".

To get the most interference situations possible, a ZigBee coordinator was installed in the position C1. The coordinator was placed aside the Wi-Fi devise that offers internet connection to the house, as shown in Fig. 17. No eligible interferences from the Wi-Fi device were found, even when it was forced to work at its maximum capacity. Only sensors S1 and S2 presented some connection problems. These sensors were at a distance of approximately 26 m from the coordinator. The interferences were the result of several walls and the elevator shaft that were in the way. The problems were solved by placing a router in the position of sensor S3 to S6.

"See Fig. 17 at the end of the manuscript".

The metering data M1 was also collected with no problem by the coordinator C1. It is possible to cover all the apartment area without the use of a router by placing the coordinator in position S8 (the entrance hall). When having interference problems it is advisable to use some of the installed ZigBee devices with the capacity to also function as routers, preferably sensors and actuators that are always connected and do not enter in sleep mode (a spotlight for example).

Additional field trials were conducted in a complex of two houses. One of the houses is a modern two floor house, while the other is a rebuilt three floor house that has one meter thick external walls (built with the local iron-rich sedimentary rocks), Fig. 18.

"See Fig. 18 at the end of the manuscript".

Several installation positions were experimented in this house, especially near the well, water pump system, cellar, timber store, crops store, garden and agricultural land. All communications were made without interferences, except when more than four meters of the old iron-rich sedimentary rocks were in the transmission line path of the ZigBee WSN. But, this was easily overcome by placing one router to enhance the signal. Other tests were also made to the ZigBee installation for crops monitoring. When interferences were found, due to the density of vegetation, the placement of the ZigBee modules in a higher position was sufficient to obtain a working WSN. A communication test was also made between the house and a farming piece of land that was 60 m away. No transmission problems were found using only one sensor.

Although in all our experimental results no interference between the ZigBee and other wireless technologies were found, even in extreme situations with several technologies in the same product kernel/box, there are some works [26] reporting a small amount of interference and offering some solutions to that issue.

Nevertheless, it should be noted that the interference between ZigBee and other wireless technologies is usually much smaller than the interference between the other wireless technologies. For instance, it has been reported [27] that the effects of interference due to Wi-Fi devices on modern instrumentation are often not negligible.

5. Conclusions

In order to make the actual electricity grid more flexible and versatile, a robust data interexchange infrastructure must be created. An overview of ZigBee devices and modules is presented in this paper, addressing also the smart grid infrastructure and the importance of smart metering. Four case studies are provided to address the most appropriate experimental methodologies for the ZigBee technology implementation. In the photovoltaic energy system, belonging to a water treatment and distribution company, no significant interference was detected in our experiments. The interference occurring was easily overcome with the help of a ZigBee router to triangulate. Several tests were made inside the control house of a wind farm, but the use of routers was not necessary in this situation. Substantial interference only occurred due to a reinforced metal door or near the substation. The use of one router was sufficient to overcome this interference. The ZigBee devices were also evaluated in a complex of eleven floors buildings and several urban homes. The interference felt, as a result of walls or the elevator shaft, was again solved by suitably placing just one router. Hence, the novel experimental results provided in this paper have clearly demonstrated the proficiency of the ZigBee devices for monitoring real-time data in distributed renewable generation and smart metering systems, making them valuable, flexible and robust assets within a smart grid.

Acknowledgments

The authors thank SMAS Vila Franca de Xira and GENERG Group for providing access to their installations, in which several field tests were implemented. Also, the authors thank the Fundação para a Ciência e a Tecnologia (FCT) and the Operational Programme for Competitiveness Factors (COMPETE), supported by FEDER funds (European Union), for Project No. FCOMP-01-0124-FEDER-020282 (Ref. FCT PTDC/EEA-EEL/118519/2010).

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Figure captions

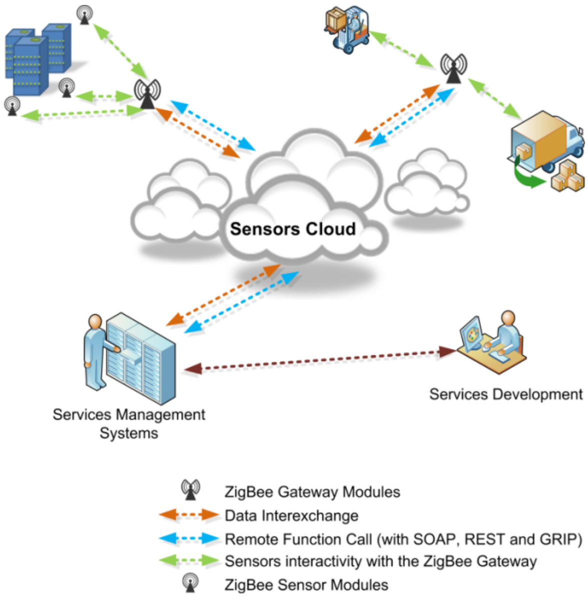

Fig. 1. Implementation of a ZigBee WSN.

Fig. 2. Smart Grid energy and data interexchange (Source: ABB 2009).

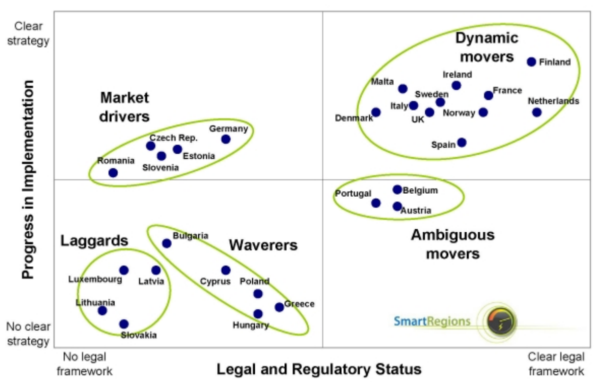

Fig. 3. Smart metering development evolution in European Countries (Source: SmartRegion 2011).

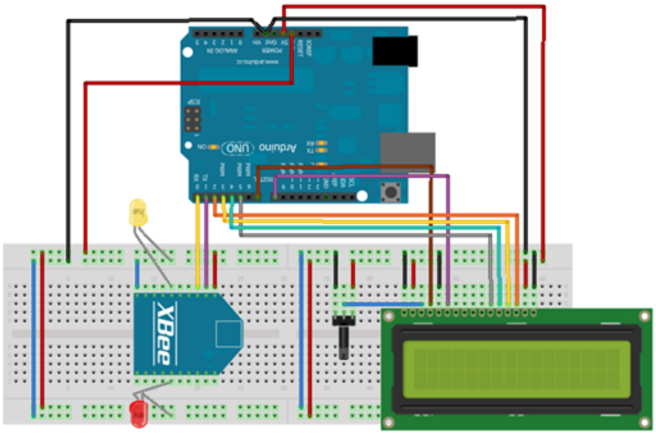

Fig. 4. ZigBee coordinator schematic.

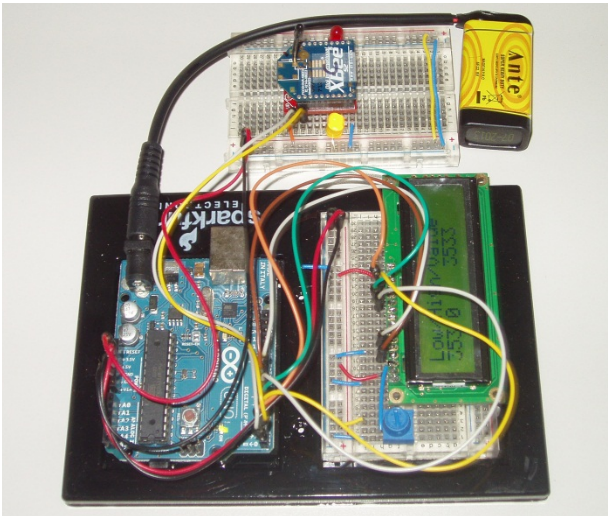

Fig. 5. ZigBee coordinator device experimentally built.

Fig. 6. Photovoltaic energy system belonging to the water treatment and distribution system (SMAS) operator.

Fig. 7. Inverter used for the grid connection.

Fig. 8. Inside the water supply installation (on the left) with the ZigBee coordinator suitably placed (on the right).

Fig. 9. Two ZigBee devices in a wind farm with over fifty wind turbines.

Fig. 10. Outside the tower of wind turbine GA 29.

Fig. 11. Inside the control house of the wind farm.

Fig. 12. Outdoor substation environment.

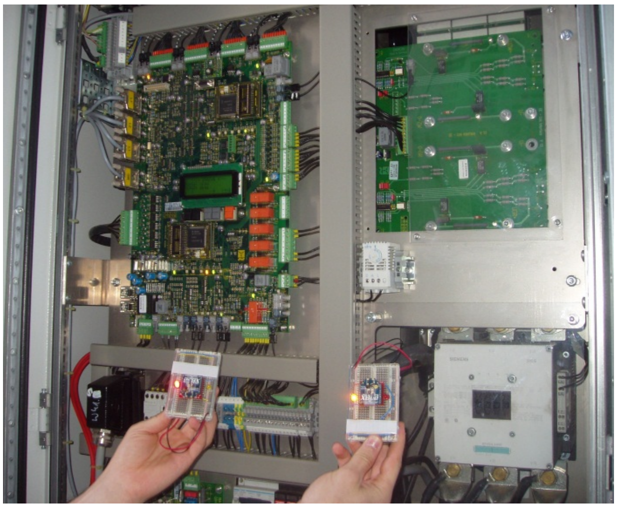

Fig. 13. Inside the tower of wind turbine GA 29, with two ZigBee devices, and near the electric components.

Fig. 14. ZigBee device placed near an electricity meter.

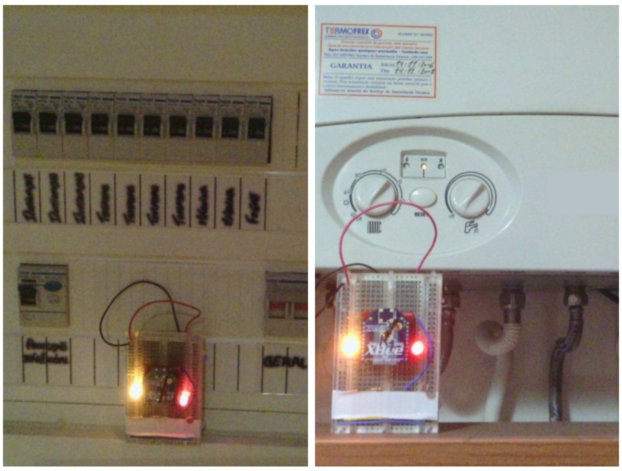

Fig. 15. ZigBee device placed near an electric board (on the left) or a gas installation (on the right).

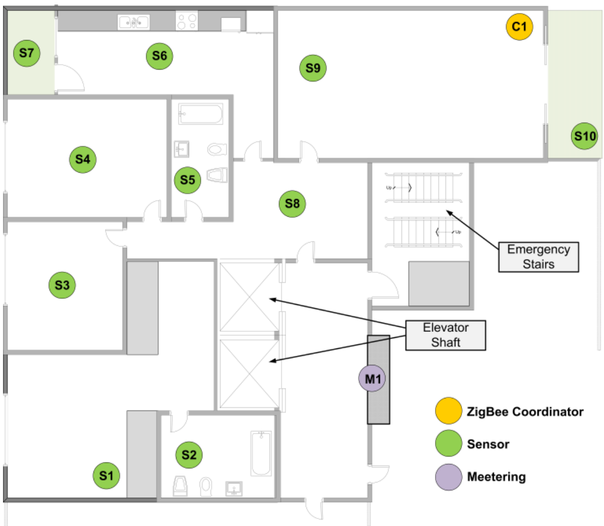

Fig. 16. Home configuration with the position of the ZigBee coordinator, sensor and metering.

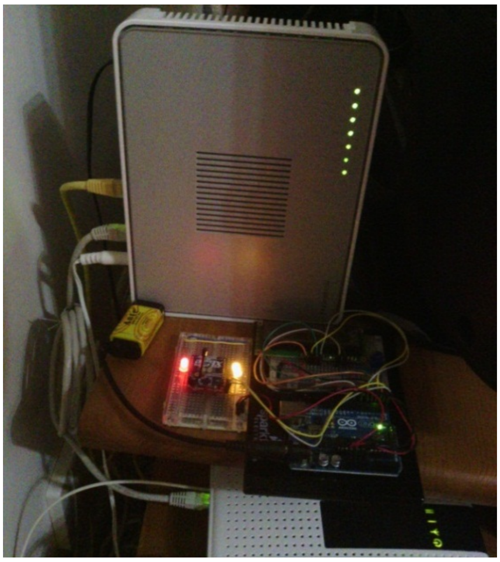

Fig. 17. ZigBee module near a Wi-Fi wireless internet access.

Fig. 18. Farm house with several ZigBee modules suitably placed.

Tables

Table 1

Comparison between three commercially available ZigBee modules

	XBee ZB	XBee-PRO ZB	XBee-PRO 868
Indoor Range	40 m	90 m	550 m
Line-of-Sight Range	120 m	1500 m / 3200 m	40 km
RF Data Rate	250 kbps	250 kbps	24 kbps
Frequency	2.4 GHz	2.4 GHz	868 MHz
Transmit Power	1.25 mW / 2 mW	10 mW / 63 mW	1 mW / 315 mW
Encryption	128-bit AES	128-bit AES	128-bit AES
Number Channels	16	15	1
Transmit Current	35 mA / 45 mA	205 mA	500 mA
Receive Current	38 mA / 40 mA	47 mA	65 mA
Topology	Mesh	Mesh	Star
Estimated Price	$17	$28	$69
Regions	Europe, USA, Australia, Canada, Japan	Europe, USA, Australia, Canada, Japan	Europe