Title	Multiradio sensing systems for home area networking and building management
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Publication date	2016-05-22
Original citation	O'Flynn, B., De Donno, M. and Magnin, W. (2016) 'Multiradio Sensing Systems for Home Area Networking and Building Management, 'SMART 2016 : The Fifth International Conference on Smart Cities, Systems, Devices and Technologies, Valencia, Spain, 22-26 May. IARIA. ISBN: 978-1-61208-4763
Type of publication	Conference item
Link to publisher's version	https://thinkmind.org/index.php?view=article&articleid=smart_2016_2_20_40015 Access to the full text of the published version may require a subscription.
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Item downloaded from	http://hdl.handle.net/10468/3928

Multiradio Sensing Systems for Home Area Networking and Building Management

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***Abstract*—Many WSN systems use proprietary systems so interoperability between different devices and systems can be at best difficult with various protocols (standards based and non-standards based) used (ZigBee, EnOcean, MODBUS, KNEX, DALI, Powerline, etc.). This work describes the development of a novel low power consumption multiradio system incorporating 32-bit ARM-Cortex microcontroller and multiple radio interfaces - ZigBee/6LoWPAN/Bluetooth LE (Low Energy)/868MHz platform. The multiradio sensing system lends itself to interoperability and standardization between the different technologies which typically make up a heterogeneous network of sensors for both standards based and non-standards based systems. The configurability of the system enables energy savings, and increases the range between single points enabling the implementation of adaptive networking architectures of different configurations. The system described provides a future-proof wireless platform for Home Automation Networks with regards to the network heterogeneity in terms of hardware and protocols defined as being critical for use in the built environment. This system is the first to provide the capability to communicate in the 2.4GHz band as well as the 868MHz band as well as the feature of multiboot capability.**

Keywords - Smart Sensing; Home Area Networks; Energy Management; Multiradio Systems.

I. INTRODUCTION

Wireless Sensor Network (WSN) systems have the potential to be ubiquitous in today's society in a myriad of applications such as Smart Homes, Building Energy Management (BEM), micro grid management, environmental monitoring and smart cities. New architectures are required to offer improved inter-operability, to improve reliability of data communications and to address the spread spectrum requirements associated with next generation sensor systems through the development of smart radio systems. Currently available platforms exist that have multiple radios but these tend to operate in a single Industrial, Scientific and Medical (ISM) band (typically 2.4GHz) – and not in combination with the 868MHz ISM Band which is ideal for the built environment due to its long range, low data rate properties.

The value of WSNs as a sensing system is clear - typically wired sensor systems are expensive to install with 70-90% of the cost of a sensor system installation relating to labor and wiring – which ranges from 40 to $2000 per linear foot of wiring [1]. A number of challenges still need to be addressed to ensure WSN technology achieves its' full potential across all application areas. An abundance of communications technologies persist within the Home Area Networking (HAN) domain, with no single technology identifying itself as the "one size fits all" solution.

The *AUT*onomic *H*om*E* area *N*e*T*work *I*nfrastru*C*ture (AUTHENTIC) project [2][3] funded by the International Energy Research Centre (IERC) [4] seeks to explore, the design and delivery of a HAN infrastructure capable of supporting opportunistic decision making pertaining to effective energy management within the home. This requires the integration of key enabling heterogeneous technologies including a variety of physical sensors within the home (temperature, contact sensors, passive infra-red), cyber sensor sources (services) outside of the home (e.g., meteorological data, energy providers dynamic pricing sites) together with effective interfacing with the smart grid beyond the home. Section I of this paper introduces the subject matter and application space associated with wireless sensing solutions for the built environment. Section II reviews some of the state of the art in current wireless sensing system technologies, with emphasis on multiradio systems. Section III describes the "Authentic Board" developed within the project. Section IV describes the multiradio functionality and Section V examines the results of initial trials and tests carried out using the system.

II. PREVIOUS WORKS

There are a variety of standards available (proprietary and non-proprietary), which are widely used within the many deployments of HAN which exist. ZigBee, Bluetooth, IEEE 802.11x (Wi-Fi) are globally recognized as references in wireless communications and go far beyond the scope of WSN. Those technologies have been developed using the license-free ISM band of 2.4-2.5GHz, although ZigBee has an implementation for the 868MHz and the latest 802.11.n standard used by Wi-Fi offers support for both 2.4 and 5GHz. Indoor range above the GHz frequency is quite limited especially for indoor applications with dense obstacles. The Wi-Fi technology surpasses those issues with higher transmission power (up to 100 times higher than ZigBee/802.15.4), which is of course not suitable for battery powered systems in low power WSN systems.

Although some manufacturers provide WSN systems using 868MHz or even 433MHz, it is more common to see them designed around proprietary technologies such as ZigBee. An interesting trade off investigated in this paper is the development of a system with the ability to adapt its communications channel to use the best radio link depending on the throughput and range requirements in any configuration.

Multiradio platforms are a subject of research for WSN as they offer some attractive characteristics and improvements over single radio WSN platforms. Multiradio systems with radios covering Wi-Fi, Bluetooth and 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks) operating at the 2.45 GHz ISM band have reported to achieve enhanced robustness, latency and energy characteristics [5]. In different implementations, multiradio systems operating at the 433MHz and 2.45 GHz ISM bands were reported [6] using a preamble sampling technique in a wakeup radio implementation showing experimental performance evaluation of a developed protocol in terms of power consumption and latency over different duty cycle values and under various amounts of traffic loads. A multiradio platform for on the body WSN applications operating in 433MHz and 868Mz is reported in [7] with focus on the platform architecture. More consideration on the issues of antenna design for such devices is found in [8] [9].

The OPAL is an example of a multiradio platform where increased performance in terms of the network realization, latency, data throughput and power consumption were achieved compared to single radio platforms [10]. The OPAL platform is a high throughput sensing module that includes two onboard 802.15.4 radios operating in the 900 MHz and 2.4GHz bands to provide communication diversity and an aggregate transfer rate of 3 Mbps. It embeds a 96 MHz Cortex SAM3U processor with dynamic core frequency scaling, a feature that can be used to fine-tune processing speed with the higher communication rates while minimizing energy consumption.

The platform described in the following sections of this paper is a novel low power consumption multiradio system incorporating 32-bit ARM-Cortex microcontroller and multiple radio interfaces - ZigBee/6LoWPAN/Bluetooth LE/868MHz platform, which features autonomous behavior to enable interoperability between systems utilizing different radio front ends. It provides a solution for network congestion in environments such as HAN and Commercial Buildings in a credit card sized form factor (see Figure 1 below). It also provides better interoperability than the usual wireless sensor devices approach, enhancing the communicability between different network entities (sensor nodes, smart meters, media, smartphones), and driving the wireless sensor networks to the smart cities application space.

III. SYSTEM IMPLEMENTATION

The aim of this system development is to provide a future-proof wireless platform for HAN with regards to the network heterogeneity in terms of hardware and protocols currently in use and under development.

A specification process was undertaken with industry partners and service providers in the area of building management – to identify the core requirements associated with a wireless system for deployment in homes and offices.

Figure 1. AUTHENTIC Credit Card Form Factor Platform.

The four main issues that need to be considered prior to selecting any unit or design approaches are: over all power consumption, cost, complete module size and user friendliness. Technical features assessed and considered included: functionality requirements as regards, actuation and control, quality of service, latency, number and types of sensors/meters and interfaces, programming methods (wireless/non wireless), power supplies/energy harvesting compatibility, radio frequency band, standards/non standards communications and data transmission range.

In conjunction with these end users, as part of our system specification, three communication standards were identified as being needed within the home area network environment: ZigBee – 2.4GHz, 6LoWPan – 2.4GHz, Bluetooth Low Energy – 2.4GHz, as well as a non-standards based ISM band 868MHz transceiver as a response to the 2.4GHz limitations identified - bandwidth congestion and data loss associated with non line of sight (NLOS) effects of the building structure limited RF range. The board has been designed around the standard ARM CORTEX-M3 based microcontroller, which offers a good trade-off between power consumption and performance. See Figure 2 for an overview of features and functionalities.

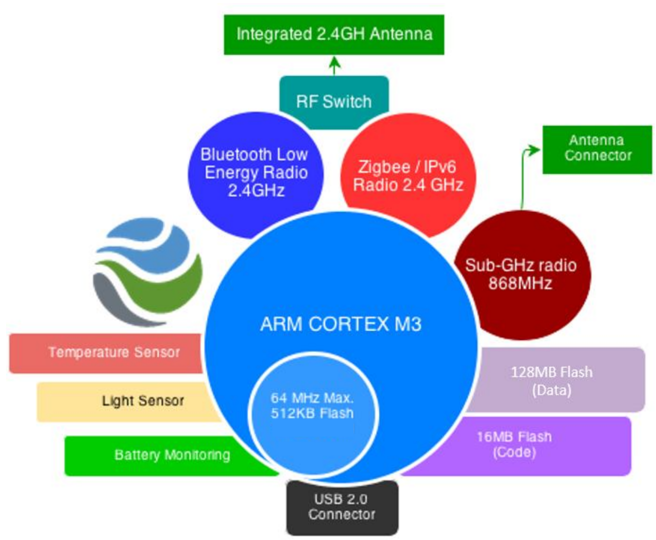

Figure 2. Block diagram of AUTHENTIC Platform functionality.

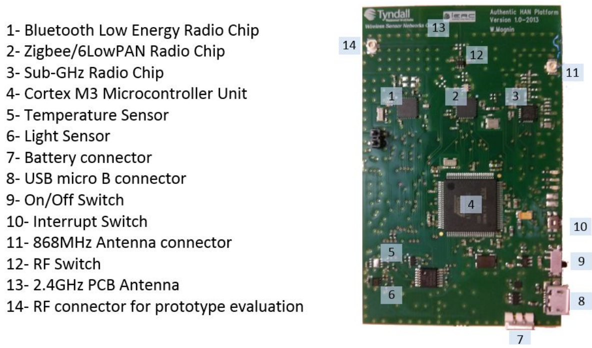

Figure 3. AUTHENTIC multiradio embedded system.

The final embedded system was designed around a credit card form factor (Figure 3) and deployed in offices and homes for preliminary tests and characterization

Microcontroller: The heart of the system is the ATMEL SAM3S8C microcontroller, a 32-bit ARM Cortex M3 Core. - 64MHz Maximum, 512KB flash, 64KB RAM, USB 2.0.

External Flash Memories: Two external flash memories: 128MB NAND flash for data logging, 16MB NOR-flash for code execution. The two memories are connected to the microcontroller External Bus Interface (EBI).

Radio Communication: The platform integrates three radio chips: Bluetooth Low Energy radio chip, (manufacturer: NORDIC, model: NRF8001), ZigBee/6LoWPAN radio chip, (manufacturer: ATMEL, model: AT86RF231), Sub-GHz radio chip (868MHz), (manufacturer: ST Microelectronics, model: SPIRIT1).

Sensors: Two sensors were interface via an I^2C interface: temperature sensor, accuracy: ±0.5°C, (manufacturer: MAXIM, model: MAX31725MTA+), light sensor, range: 0.045 Lux to 188,000 Lux, (manufacturer: MAXIM, model: MAX44009EDT+T). These are used for detecting in home activity monitoring occupancy through lighting usage.

Battery: The battery used is a lithium prismatic battery with a capacity of 1.3mAh which is recharged through the USB port or through the use of energy harvesting systems compatible with the built environment [11].

IV. MULTIRADIO FUNCTIONALITY

A. *Communication Architectures using Multiradio systems*

In the context of "crowded radio frequency spectrum", a wireless sensor network composed with a number of the proposed devices' architectures can automatically adapt to the most reliable frequency communication channel based on the local interferences. This type of architecture has some interesting commercial applications for interoperable networks, HAN's, commercial buildings and smart cities. Compared to single-end radio devices, it has the potential to provide increased connectivity in deployment, and can potentially reduce the interference impact on the network as the system can hop from ISM band to ISM band in an autonomous and opportunistic manner.

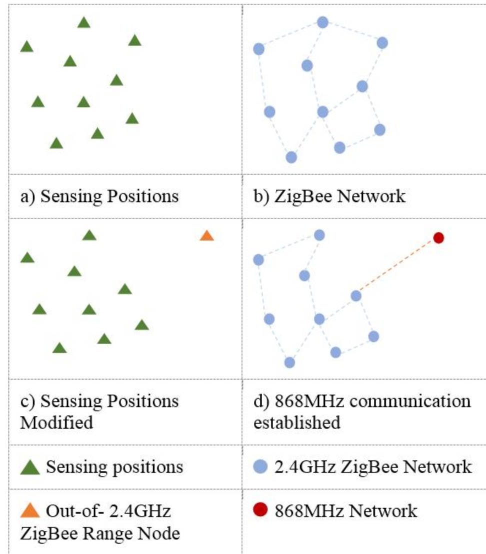

Figure 4. AUTHENTIC multiradio system in operation

By developing smart mechanisms for multi-protocol routing between the different radios, this architecture can potentially reduce the number of repeaters (and thus the infrastructure cost) compared to a standard single ended radio platform. In addition, multiradio systems provide better interoperability with Off-The-Shelf wireless devices, many of which operate on a variety of different standards and which may constitute a typical smart home deployment.

From a research point of view, such a platform can be used to develop and evaluate firmware/wireless protocols using different frequency bands.

The multiradio concept is illustrated in Figure 4 and shows how, by jumping between the 2.4GHz and 868MHzfrequency bands, a connection can be made between remote clusters of ZigBee nodes which are in different locations or separated by a congested spectrum making communication at 2.4GHz difficult.

Thus the network automatically switches to the 868MHz frequency in order to maintain communication with the out of range node. In that case, one node from the first cluster will act as a virtual "dual sensing" node, providing two inputs to the ZigBee Network.

B. *Multiradio Aspect*

The Bluetooth and 868MHz multiradio functionality has been tested as a proof of concept in a HAN as part of the AUTHENTIC deployment in office environments and in homes (for open field testing, the system was deployed temporarily outside).

To evaluate the capabilities of the multiradio functionality, the remote node sends data (light, temperature or other peripheral sensor) to the base station using the 868MHz radio or the 2.4GHz ZigBee network. The base station then sends the received data to a Smart Phone/HAN gateway using the Bluetooth interface that displays the data stream (in this case, temperature and light level from the remote sensor) as shown in Figure 5.

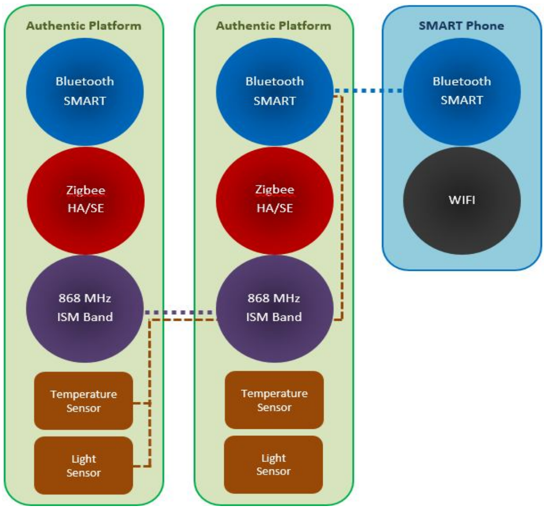

Figure 5. AUTHENTIC multiradio system

C. Multiboot - Autonomous system Implementation

Multiboot capability enables the system to boot up and run according to various boot images [12] [13] which are stored in various sectors (region) of memory see Figure 6.

To facilitate energy savings at an embedded system level, the multiboot configuration of the system will allow the platform to host two different applications and jump between them (via a boot loader). The applications can and will use different radios in future deployments, which will be useful for overcoming transmission issues in a congested/noisy environment. The targeted example is the mote running a ZigBee 2.4GHz application and an 868MHz application. Failing to transmit data at 2.4GHz due to electromagnetic effects or long range requirements, the node would switch to the 868MHz application to operate in a less congested ISM band. This behavior would be coordinated among the network nodes in protocols under development. In this case, the idea is to allocate memory regions to specific applications.

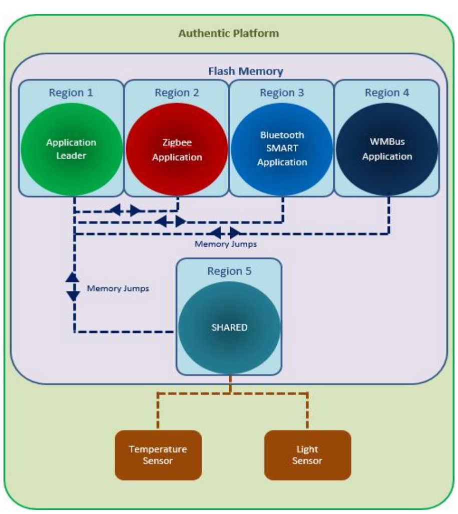

Figure 6. AUTHENTIC Multiboot reconfigurability

The **Multi-Application Software Management** tool acts as a main application that we will call "**Leader**". The **Leader** is programmed in a specific area of the memory and will act as what is commonly known as a Bootstrap Loader. The particular boot state functionality can be associated with a range of communications modalities say ZigBee, Bluetooth or Wireless Modbus according to application requirements associated with energy consumption, latency or Quality of Service.

The **Leader** can access any location of the memory. The applications that will contain the required functionalities of the system (e.g., sensing, communication) will be described as "**Users**". The **Leader** can then grant the leadership to the different **Users** that will need to return the leadership to the **Leader** (different solutions are possible for the latter).

The **Leader** will provide API (Application Programming Interface) in order to modify intrinsic parameters of the system (e.g., system clock frequency, timers etc.). Thus, this functionality will considerably reduce the complexity of the development from the user developer's point of view.

From a smart home/building management system deployment perspective, it will provide an essential software management tool for multiradio platforms.

V. RESULTS

A. AUTHENTIC Board Power Characterization

To carry out theses energy consumption tests the following modalities were implemented as shown in Table I.

TABLE I. SYSTEM POWER CONSUMPTION IN DIFFERENT MODES

Symbol	**Operational Mode Measured**	**Value**	**Unit**
ITX868	Current consumption in TX mode 868MHzmodule, POUT = +12 dBm, all components on	43.98	mA
Isb868	Current consumption in standby mode 868MHzmodule, all components on	28.24	mA
ITXBLE, 0dBm	Current consumption in TX mode BLE module, POUT = 0 dBm, all components on	24.80	mA
IsbBLE	Current consumption in standby mode (between 2 transmissions) BLE module, all components on	17.29	mA
ITX, ZigBee1	Current consumption in TX mode ZigBee module, POUT = +3 dBm, all components on, 1 led on	64.07	mA
ITX, ZigBee2	Current consumption in TX mode ZigBee module, POUT = +3 dBm, all components on, 1 led off	71.12	mA
Isleep1	Current consumption in sleep mode (microcontroller) and all the other components on	15.73	mA
Isleep2	Current consumption in sleep mode (microcontroller) and all the other components off	3.18	mA
Isleep3	Current consumption in deepest sleep mode (microcontroller) and all the other components on	3.1	mA
Isleep4	Current consumption in deepest sleep mode and components off / removed	3.5	µA

The MCU is programmed to turn on all the devices, setting the output power of the module to (+12 dBm for 868 MHz module, 0 dBm for BLE, +3 dBm for ZigBee), start the transmission of a single packet (1 byte length) and then put it in standby mode. Sleep mode tests include the MCU turning on all the devices before going into sleep mode, turning off all the devices and entering sleep mode, turning on all the devices and entering deepest sleep mode and turning off all the devices and goes into deepest sleep mode.

For the 868 MHz tests, GFSK (Gaussian frequency-shift keying) modulation with the Gaussian filter "BT Product" set to 1 was used. For the Bluetooth LE modules the default Gaussian filter used is 0.5. For the ZigBee module quadrature phase-shift keying (QPSK) modulation was used. Table I shows the results of all tests in different modes. These provide the building blocks for developing low-power networking algorithims for optimising the lifetime of the WSN systems and QoS parameters.

B. Multiradio Range Test Comparison

1) Indoor Non Line of Sight (NLOS) range testing

This section focuses on the NLOS testing of the 868 MHz, Bluetooth and ZigBee radio modules on the AUTHENTIC Board. Two boards are used: one acts as a sensing node and one as a Base Station. The node reads data from the temperature sensor as well as received signal strength indication (RSSI) values. This is then sent to the Base Station where it is converted into a value expressed in °C (minimizing energy consumption associated with processing on the node), which is in turn sent to our visual interface (a smartphone connected via Bluetooth). The test took place in an office environment consisting of open plan cubicles, closed offices, coffee dock facilities and meeting rooms in a simulated "home environment". The node (represented by the star) was kept stationary while the base station and the smartphone moved around the entire area for data gathering at the different frequencies under test. In Figures 7, 8, 9, the areas where the data is received perfectly are reported in green, in orange the areas where the signal is poor and the data is received intermittently, in red the areas where there is no signal and data is not received.

Figure 7. 868MHzrange test

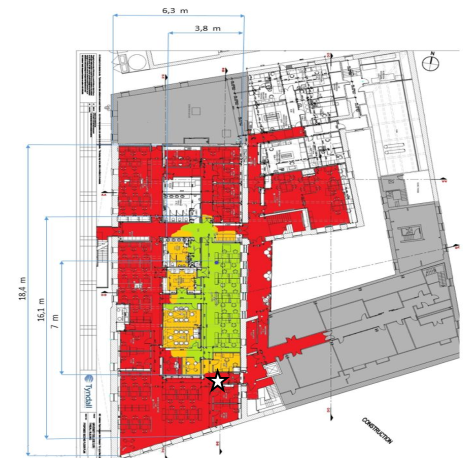

Figure 8. Bluetooth range test

Figure 9. ZigBee 2.4GHz range test

Theory would suggest that the range associated with lower frequency (868MHz) ISM bands would significantly outperform higher frequency ISM bands (2.4GHz). In this experiment, the difference is little more than a 10% improvement see Table II. We expected 868MHz to be much better than ZigBee, a possible reason (under investigation) is that the 868MHz data rate (500 kbps) is higher than the ZigBee one (250 kbps) and there is a tradeoff between the range and the data rate. Moreover, the modulation used by the modules are different: the value of Eb/N0 (noise power per unit bandwidth) of the offset-QPSK is less than that of the GFSK; this means that the bit error rate is better for the ZigBee module operating at 2.4GHz. To improve the 868MHz range, it is possible to increase the power of the module (it can reach +16 dB) and reduce the data rate. Further experiments are under way to validate this.

TABLE II. COMPARISON OF RANGE FOR INDOOR NLOS TESTS

Radio	Appoximate Area Covered	Max. distance (Line of sight)
868 MHz	130.4 m^2	11.4 m
Bluetooth LE	60.04 m^2	7 m
ZigBee	108.6 m^2	10.6 m

2) *Outdoor Line of Sight (LOS) range testing*

An open field is one of the simplest and most commonly used environments to do RF range tests. In this section tests for the three modules on the AUTHENTIC Board (868 MHz, Bluetooth, and ZigBee) are reported. The tests took place in a sports field in University College Cork, which offered a long range LOS measurement

868 MHz: To test the Sub-GHz module, two AUTHENTIC boards were used, one as Node Remote and one as Base Station. The first reads data every four seconds from the temperature sensor and sends it to the Base Station. The maximum range measured was 193m.

Bluetooth: For this test two devices were used: one AUTHENTIC Board and a smartphone. The board was left stationary and the smartphone was moved around the area checking if the connection was still available or not. The maximum LOS distance measured was 18.4m.

ZigBee: To test the ZigBee module, two AUTHENTIC boards (one as Trust Center and one as Occupancy Sensor) were used along with a RF231USB-RD USB Stick (as Remote Control) were used. The Trust Center creates the network and the other two devices join it. After this, the Occupancy Sensor reads the value of the LED (on/off) and sends it every four seconds to the Remote Control that moves around the area. The maximum range measured was 193m.

The maximum distance measured in Line of Sight for both the ZigBee and 868MHz system was 193m, but this value could be greater and additional tests need to be carried out to establish the maximum range for each. The maximum range achieved was due to the presence of physical obstacles (walls/buildings, which would have interfered with the LOS measurements at the maximum extremity of the test location. The results are tabulated in Table III.

TABLE III. COMPARISON OF RANGE FOR OUTDOOR LOS TESTS

Radio	Max. distance (Line of Sight)
868MHz	193m *
Bluetooth LE	18.4m
ZigBee	193m *

* Limit of the field measurement not the technology

VI. CONCLUSIONS & FUTURE WORK

This work describes the development and preliminary characterization of a novel low power consumption multiradio system incorporating multiple radio interfaces - ZigBee/6LoWPAN/Bluetooth LE/868MHz platform. It provides a solution for network congestion in environment such as Home Area Network and Commercial Buildings in a credit card sized form factor. The multiradio sensing system shows the potential for such systems to improve interoperability between the different wireless technologies enhancing the communications between heterogeneous network entities (Sensor Nodes, Smart Meters, Media, Smart Phones), and driving the Wireless Sensor Networks use case in the built environment The configurability of the system can increase the range between single sensor points and can enable the implementation of adaptive networking architectures of different configurations.

Additional characterization and optimization of the system in a variety of environments is underway and development of frequency hopping protocols to maximize the potential of the multiradio system and its possibilities to maximize system lifetime of a WSN in a Smart Home or office environment through the development of networking protocols leveraging off the platforms capabilities.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of Enterprise Ireland and the International Energy Research Centre (IERC) for funding the AUTHENTIC project (TC20121002A/B). This publication has emanated from research supported in part by Science Foundation Ireland (SFI) and is co-funded under the European Regional Development Fund, Grant Number 13/RC/2077-CONNECT.

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