CORA Cork Open Research Archive
Cartlann Taighde Oscailte Chorcaí

Title	Multiradio, multiboot capable sensing systems for home area networking
Authors	O'Flynn, Brendan;De Donno, Marco;Magnin, Wassim
Publication date	2016
Original Citation	O'Flynn, B., De Donno, M. and Magnin, W. (2016) 'Multiradio, Multiboot capable sensing systems for Home Area Networking', International Journal on Advances in Networks and Services, 9 (3&4), pp. 96-106. http://www.iariajournals.org/networks_and_services/
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://www.iariajournals.org/networks_and_services/netser_v9_n34_2016_paged.pdf
Rights	2016, © Copyright by authors, Published under agreement with IARIA - www.iaria.org
Download date	2026-11-06 22:43:06
Item downloaded from	https://hdl.handle.net/10468/3927

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Multiradio, Multiboot Capable Sensing Systems for Home Area Networking

Brendan O'Flynn, Marco De Donno, Wassim Magnin
Tyndall National Institute
University College Cork
Cork, Ireland

email: brendan.oflynn@tyndall.ie. marco.dedonno@tyndall.ie, wassim.magnin@tyndall.ie

***Abstract*—The development of Wireless Sensor Networking technology to deploy in smart home environments for a variety of applications such as Home Area Networking has been the focus of commercial and academic interest for the last decade. Developers of such systems have not adopted a common standard for communications in such schemes. Many Wireless Sensor Network 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, KNX, 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/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. A description of the system operation and potential for power savings through the use of such a system is provided. Using such a multiradio, multiboot capable, system can not only allow interoperability across multiple radio platforms in a Home Area Network, but can also increase battery lifetime by 20 – 25% in standard sensing applications.**

Keywords - Smart Sensing; Low Power Consumption Protocols, Home Area Networks (HAN); 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), Home Area Networking (HAN), micro grid management, environmental monitoring and smart cities. New architectures, such as those described in the conference paper [1] and from which this paper evolved, 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.

This type of architecture has some interesting commercial applications for interoperable networks, Home Area Networks, 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 because the system can hop from ISM band to ISM band in an autonomous and opportunistic manner. The development of multiradio sensing architectures lends itself to interoperability between the different technologies that typically make up a heterogeneous network of sensors.

The value of WSNs as a sensing system is clear when you compare them to traditional wired sensing systems. 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 [2]. As such, the wireless nature of WSN technologies makes them easier and cheaper to deploy than wired technologies.

However, 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 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 [3][4] funded by the International Energy Research Centre (IERC) [5], sought to develop and deploy a HAN infrastructure capable of supporting opportunistic decision making pertaining to effective energy management within the home. This required 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. As part of the AUTHENTIC project (final demonstrators were

presented in 2015) the WSN group at Tyndall were developing the embedded systems and communications platforms to sense and transfer data in the built environment. The platform developed enables communications between the heterogeneous sensing systems that typically make up a HAN scenario in a power efficient implementation.

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 [1]. Section IV describes the multiradio functionality and Section V examines the results of initial range testing trials and tests carried out using the system to investigate power consumption characteristics of the platform. Section VI investigates the power savings enabled by this multiradio, multiboot platform, through the implementation of different communications protocols based on the system level tests carried out in Section V. Section VII concludes the work and outlines some directions for future research in this area.

II. PREVIOUS WORKS

There are a variety of standards available (proprietary and non-proprietary), which are widely used within the many deployments of HAN that exist. ZigBee, Bluetooth LE (Low Energy), 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 deployments.

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 [6]. In a variety of implementations, multiradio systems operating at the 433MHz and 2.45 GHz ISM bands have been reported which use a preamble sampling technique in a wakeup radio implementation [7]. These multiradio platforms have been used to evaluate the performance of communications protocols in terms of power consumption and latency over different duty cycle values and under various amounts of traffic loads. Kusy [8] reports on the development of a new dual radio network architecture to improve communication reliability in a wireless sensor network, but the approach was limited to a single channel implementation, where the 900MHz and 2.4GHz radios were used in parallel rather than in conjunction with power saving protocols. A multiradio platform for on the body WSN applications operating in 433MHz and 868Mz is reported in [9] with focus on the platform architecture. More consideration on the issues of antenna design for such devices is found in [10] [11]. A comprehensive survey of MAC protocols is given by Jurdak et Al in [12]. They survey, classify, and analyze 34 MAC layer protocols for wireless ad hoc networks, ranging from industry standards to research activites.

The BtNode V3 [13] platform features two radios. It incorporates a Chipcon CC1000 low power radio (433-915 MHz) and also has an additional ZV4002 Bluetooth radio (2.4 GHz) as shown in Figure 1.a. Similarly the Shimmer mote [14] and the Wasp Mote [15] feature a CC2420 IEEE 802.15.4 radio and can also be configured with an optional Bluetooth radio shown in Figure 1.b and Figure 1.c respectively. The Wasp Mote also has separate 868MHz and 900MHz radio modular plug-in boards however, in this instance only a single radio module can be operated at a time and true multiradio operation is not feasible. Similarly, the Tyndall Mote (Figure 1.d), has the capability for adding multiple radios. With the Tyndall mote, because of the planar implementation, several different radios could be stacked on top of each other and operate simultaneously.

The AUTHENTIC board described in this publication is not only a radio sensing platform but it can also be a repeater increasing the range of the network. Moreover, at the same time, the user can connect to each single platform in the network using a tablet or a smartphone via Bluetooth (for maintenance or data visualization).

The AUTHENTIC board has been designed with interoperability in mind, it can be used in existing deployments that use ZigBee or 868MHz protocols, to improving the network range without increasing the interference. From a protocol perspective, each board can work as an end node or base station/coordinator as well. In fact, if there are some changes in the network one node can reboot and operate as in base station mode using its multiboot functionality.

Similarly, the OPAL platform 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 [16]. The OPAL platform is a high throughput sensing module that includes two onboard 802.15.4 radios operating in the 900MHz 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.

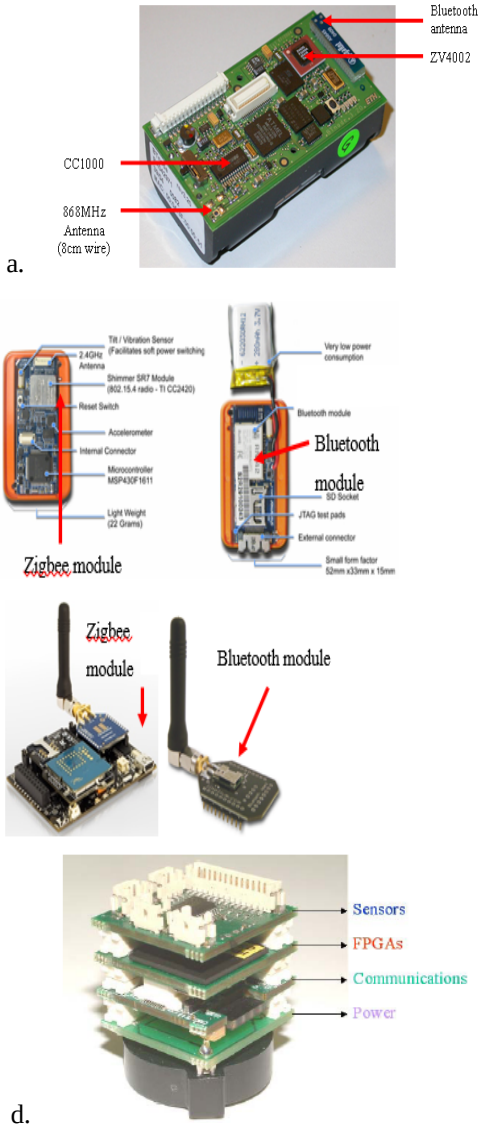


Figure 1. Multiradio systems. a) Dual Radio BTnodeRev3 b) Dual Radio Shimmer c) Wasp Mote ZigBee & Bluetooth Modules d) The Tyndall 25mm modular system

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.

The platform described in the following sections of this paper is a novel low power consumption multiradio system incorporating a 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 shown in Figure 2. 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.



Figure 2. 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.

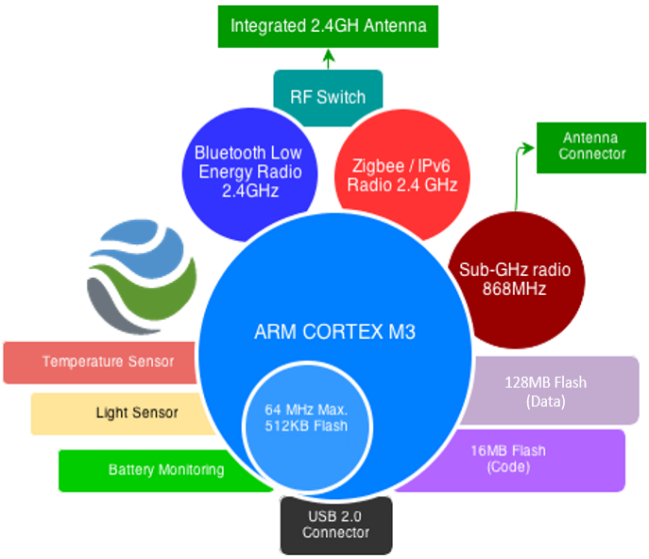


Figure 3. Block diagram of AUTHENTIC Platform functionality.

In conjunction with these end users, as part of our system specification, three communication standards were identified as being needed within the HAN 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 3 for an overview of features and functionalities.

The final embedded system was designed around a credit card form factor (shown in Figure 4) 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 interfaced 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 1300mAh, which is recharged through the USB port or through the use of energy harvesting systems compatible with the built environment [17].

1- Bluetooth Low Energy Radio Chip
2- Zigbee/6LowPAN Radio Chip
3- Sub-GHz Radio Chip
4- Cortex M3 Microcontroller Unit
5- Temperature Sensor
6- Light Sensor
7- Battery connector
8- USB micro B connector
9- On/Off Switch
10- Interrupt Switch
11- 868MHz Antenna connector
12- RF Switch
13- 2.4GHz PCB Antenna
14- RF connector for prototype evaluation

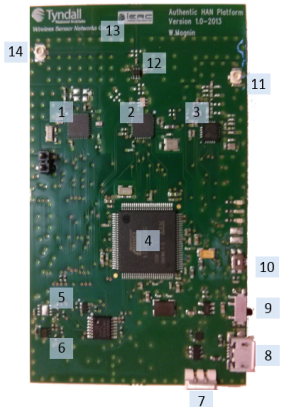


Figure 4. AUTHENTIC multiradio embedded system.

IV. MULTIRADIO FUNCTIONALITY

In this section the functionality of the AUTHENTIC platform is presented in terms of its communication architectures, the multiradio and multiboot capabilities embedded in the system.

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.

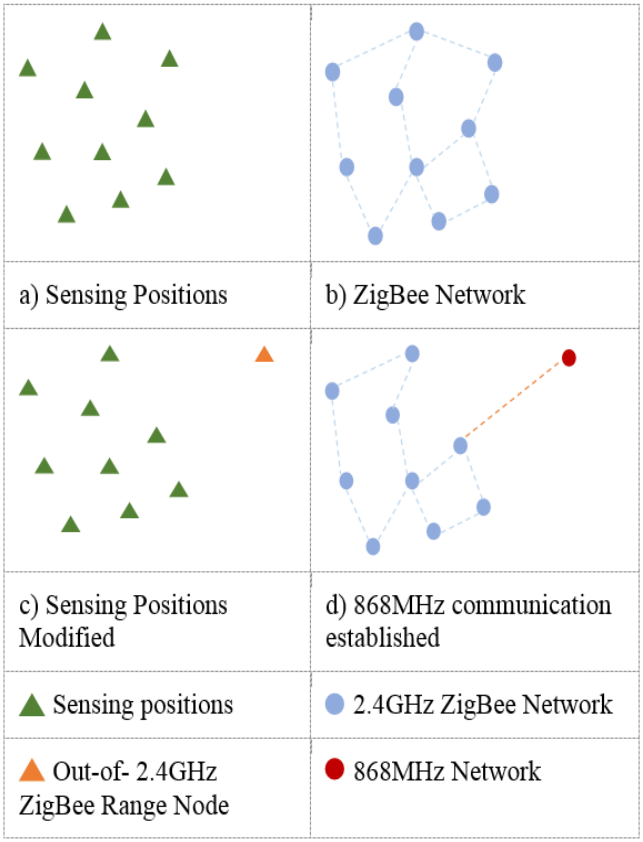


Figure 5. AUTHENTIC multiradio system in operation

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 5 which shows how, by jumping between the 2.4GHz and 868MHz frequency 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 6.

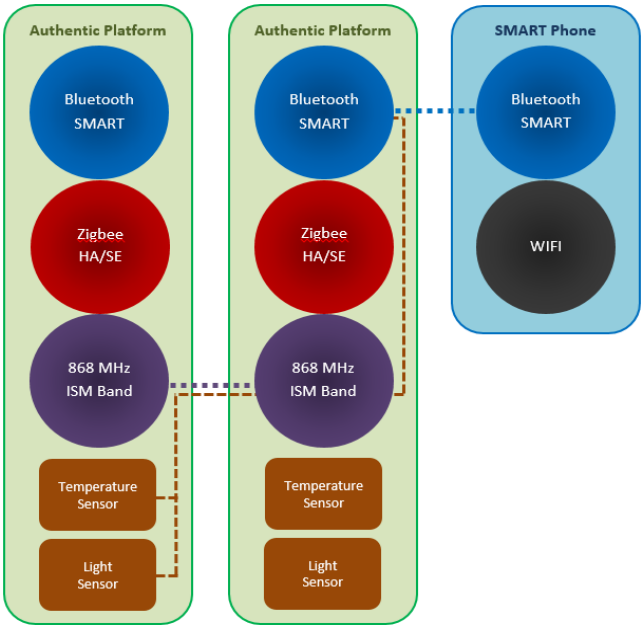


Figure 6. AUTHENTIC multiradio system

C. Multiboot - Autonomous System Implementation

Multiboot capability enables the system to boot up and run according to various boot images [18] [19], which are stored in various sectors (region) of memory – see Figure 7.

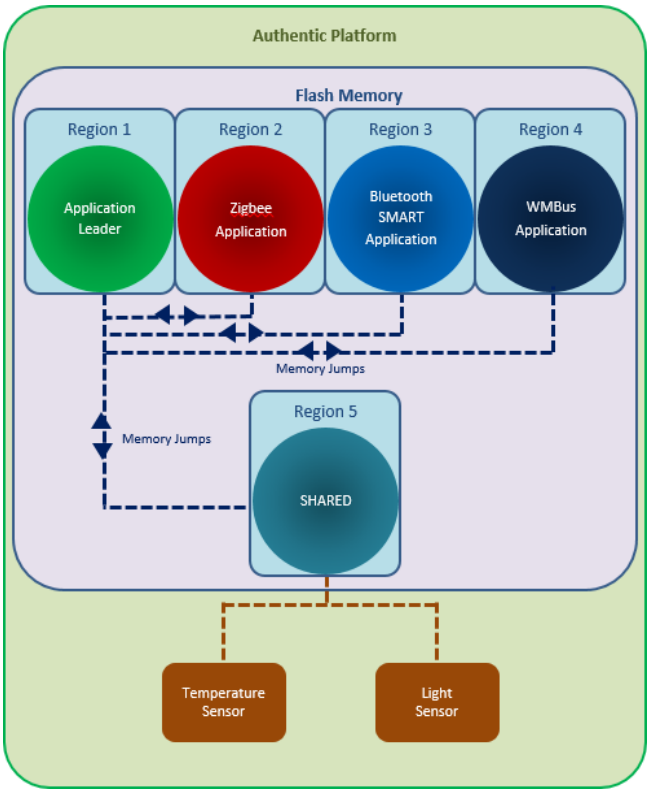


Figure 7. AUTHENTIC Multiboot reconfigurability

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.

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 an 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 the 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
ITX_{868}	Current consumption in TX mode 868MHz module, POUT = +12 dBm, all components on	43.98	mA
Isb_{868}	Current consumption in standby mode 868MHz module, all components on	28.24	mA
ITX_{BLE} 0dBm	Current consumption in TX mode BLE module, POUT = 0 dBm, all components on	24.80	mA
Isb_{BLE}	Current consumption in standby mode (between 2 transmissions) BLE module, all components on	17.29	mA
ITX, ZigBee 1	Current consumption in TX mode ZigBee module, POUT = +3 dBm, all components on, 1 led on	64.07	mA
ITX, ZigBee 2	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 going 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 8, 9, 10, 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.

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).

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

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 were carried out to validate this (as shown in Table III).



Figure 8. 868MHz range test



Figure 9. Bluetooth LE range test



Figure 10. ZigBee 2.4GHz range test

2) Sub-GHz range improvement.

To improve the 868MHz range, 3 solutions have been adopted: the output power of the sensing node was increased up to +12 dBm (initially +11dBm). In addition, the data rate was reduced to 100 kbps (from 250 kbps). Finally, the GFSK modulation with BT product was set to 0.5 (from 1). BT is the Bandwidth Time. It is the product of adjacent signal frequency separation and symbol duration. A BT product of 0.5 corresponds to the minimum carrier separation to ensure orthogonality between signals in adjacent channels. The beneficial result of this is the signal on one frequency channel does not interfere with the signal on the adjacent frequency channel.

The sub-GHz radio chip uses an external crystal oscillator that provides a clock signal for the frequency synthesizer. The channel center frequency has been programmed to be 868MHz. So as to ensure that this is the actual frequency used, it was measured using a Spectrum Analyser.

We measured that the two boards in the deployment (remote multi radio node and multi radio base station) send and receive data at 868.027 MHz (+10.70 dBm) and 868.0181 MHz (+11.02 dBm) respectively. This is found to be due to the crystal inaccuracy. To compensate the inaccuracy, a correction term (f_{offset}) has been implemented in the firmware to ensure that the frequency for send and receive is exactly set to 868MHz.

$$f_{offset} = \frac{f_{XO}}{2^{18}} \cdot FC_OFFSET$$

Where f_{XO} is the frequency of the crystal oscillator (52MHz) and ***FC_OFFSET*** is a 12-bit integer set by the FC_OFFSET registers of the radio chip.

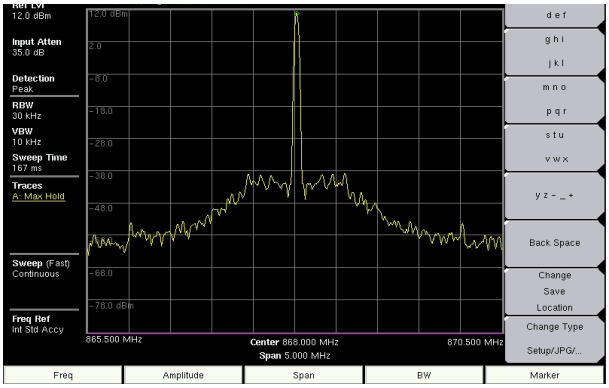


Figure 11. Output power.

After this compensation, the 2 boards had the center frequency at 868.00MHz (Figure 11) and another range test has been made in the same environment of the previous tests with 2 AUTHENTIC boards (one as node remote and one as base station) and the result has been reported in Figure 12 and Table III below showing the maximum range obtained using the 868MHz radio.



Figure 12. 868MHz range test after compensation

As can be seen from a comparison with the initial set of results reported in [1] and shown here in Table II, we achieved an improvement of 60% in performance (area covered) with the new configuration settings for the AUTHENTIC boards operating in the 868 MHz band.

TABLE III. RANGE TESTING 868 MHZ BAND USING OPTIMISED CONFIGURATION SETTINGS

Radio	Approximate Area Covered
868MHz (Test 1)	130,4 m^2
868MHz (Test 2)	211,5 m^2

3) Outdoor Line of Sight (LOS) range testing

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

868MHz: 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). 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 IV.

TABLE IV. 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. AUTHENTIC MULTI HOP PROTOCOL IMPLEMENTATION

The AUTHENTIC network has been designed to be an auto configurable network, this means that the network is autonomous in operation and has the capability to reconfigure itself. It is composed of one base station (that acts as both a router and gateway) and sensor nodes (sensing nodes that read data from the sensors on board and send the sensor data values to the base station/gateway) as shown in Figure 13.

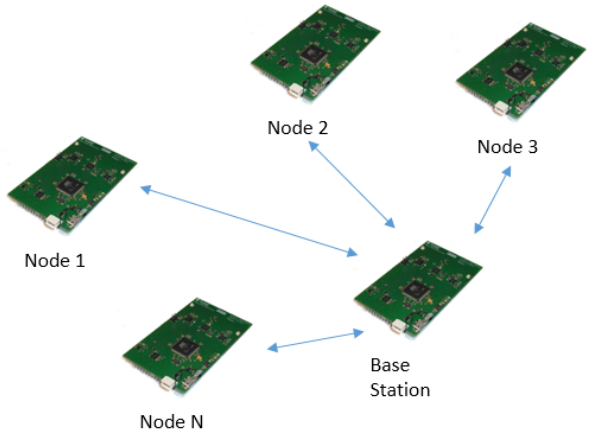


Figure 13. The AUTHENTIC network topology

At system start up, the base station creates a sub-1GHz network with the sensor nodes by transmitting a broadcast message to the nodes and waiting for their reply.

When the node receives the broadcast packet, it saves the base station's address in its memory and replies with an ACK to confirm that it has received the message.

When the base station receives the ACK, it checks the Received Signal Strength Indication (RSSI) to be sure that the link with the node is a robust one. If the RSSI value is higher than the threshold (it is taken to be -75 dBm), then the base station saves the node's address in its list of the sub-1GHz addresses, so as to be able to build an appropriate routing table. If the RSSI value is lower than the threshold, the base station sends another message to the node in order to change the radio communication to ZigBee. The default start up mode is in the 868MHz band operation mode. Two possible factors can affect the RSSI value: interference and the distance between the node and the base station. In these cases it is better to switch to another frequency.

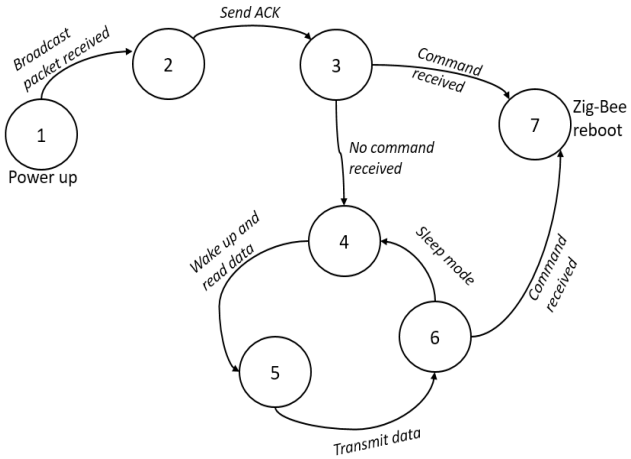


Figure 14. Node's state machine

The node goes into RX mode every time it sends a packet to the base station in order to receive the command to switch to ZigBee. The protocol state machine for the node is shown in Figure 14. The node, after sending the ACK message regarding the broadcast packet, goes into RX mode for a certain period (it is taken for the purposes of these experiments to be 1 second). During this period the only message that it can receive is the command to change its communication to ZigBee due to the RSSI level measurements taken. If so, it will reboot (using the multi boot functionality described in [1]) with the ZigBee application and waits for the creation of the ZigBee network.

If the node doesn't receive any command from the base station it assumes that it is part of the sub-1GHz (868MHz) network, and goes into sleep mode (to reduce power consumption) for a random period between 4 and 5 minutes (T_{sleep}). The node then wakes up, reads the data from the sensors on board (temperature and light level) and sends them to the base station. Once the data packet is sent, the node again enters in RX mode for 2 seconds so as to receive an appropriate command from the base station, after that it goes into sleep mode for T_{sleep}, then it wakes up, sends the sensors readings and so on.

T_{sleep} is a randomly assigned value to avoid the case that all the nodes send their sensor readings at the same time. This will reduce the probability of packet collision between the transmissions with the resultant requirement for retransmissions and increase in associated energy consumption.

The base station, after the broadcast message, communicates with each node that has replied to the broadcast, and saves all their addresses in 2 lists, one for the sub GHz network (that contains the nodes' addresses with RSSI higher than the threshold) and one for the ZigBee network (that contains the nodes' addresses with RSSI lower than the threshold). Based on these tables, the coordinator is in a position to develop an appropriate network structure. The sub GHz network is created first, after which the base station starts the creation of the ZigBee network. Once the two networks have been defined, the basestation enters sleep mode to save power. The system can be woken up by receiving sensor data messages from the nodes associated with the 2 networks created. This wake up is instigated by an interrupt based on a received data packet used to wake the microcontroller up out of standby mode.

For each message received, the base station sends the sensor data to a GUI enabled device connected via the Bluetooth interface on the AUTHENTIC Board (to any standard smartphone, tablet, PC etc.). The GUI displays data in real time from the different nodes and stores these in an associated database for analysis. The base station checks if the RSSI value of that node is higher or lower than the threshold (in this case -75 dBm). Only if it is lower than -75 dBm will the base station send a message to the node in order to switch to ZigBee network. When the node receives this command it sends an ACK to the base station to confirm that the message has been received and it reboots with the ZigBee application mode operational.

When the base station receives the ACK, it removes the node's address from the sub GHz addresses list and adds it to the ZigBee addresses list. The packet structure is shown in Figure 15.

Preamble	*Sync*	*Length*	*Dest. Address*	*Source Address*	*Control*	*Seq. No.*	*ACK*	*Payload*	*CRC*

Figure 15. The AUTHENTIC Board Zigbee packet structure

Where:

- Preamble is a signal to synchronize transmission timing and it is a programmable field from 1 to 32 bytes;
- Sync is the synchronization word;
- Length is the packet length;
- Dest. Address is the destination address and can be set to a single, broadcast or multicast address;
- Source Address is the address of the transmitting board;
- Control is the control field of the packet;
- Seq. No. contains the sequence number of the transmitted packet. It is incremented automatically every time a new packet is transmitted;
- ACK is the acknowledgement field. If set to 1 means that it is the acknowledgement packet;
- Payload is information data;
- CRC is the error detecting code to detect errors in the data.

The base station sends periodically (every 15 minutes) the general broadcast message in order to contact new nodes that did not reply at the first message or to contact any of the nodes that need to reboot so they can join the network. Nodes that are already in the network will ignore the message.

The use of this protocol shows the interoperability between the different wireless technologies (Bluetooth, ZigBee, and 868MHz). It is proposed that this system is a solution for network congestion because it reduces interference in one particular frequency band. If interference is encountered in one band then the system simply changes the operational ISM band to avoid it.

It is also a good solution to reduce power consumption associated with an individual nodes' operation. In the first instance, power savings are enabled due to the fact that the nodes and the base station are in low-power sleep mode if they don't need to transmit data. Moreover, since the base station is monitoring the RSSI signal levels, redundant and energy wasteful transmissions are eliminated (in the case that the node continues to transmit data but the base station can't receive them - because it is out of range or there is too much interference in the network).

An evaluation of potential power savings associated with the new protocol has been carried out regarding a network composed of one Base Station and three nodes and based on the power consumption reported in Table I, assuming to power the boards with a 3V battery, to transmit data every 5 minutes and then go in sleep mode.

In a scenario where three nodes join the sub-1GHz network and when the RSSI level referring to one node is lower than the threshold it joins the ZigBee network, the estimated power consumption of the Base Station is 52.13mW and 14.43mW for a single node.

As previously outlined, the Base Station is in standby mode when it is not transmitting or receiving and the nodes go into sleep mode after sending the data read from the temperature and light sensors.

In a single radio scenario, where only the ZigBee network is available, it can happen that the nodes send the sensors data to the Base Station but it cannot receive them because of the interferences or long range issues, so the nodes transmit uselessly wasting power. In this case the estimated power consumption of the Base Station is 55.87mW and 16.83mW for a single node.

System energy consumption for the multiradio platform was calculated based on a model which was developed using empirically derived power measurements. These measurements are reported in Table I, and are based on the board being powered by a 3V battery. The operational duty cycle for the sensor nodes was selected to be 5%. The system is considered to be in sleep mode for the rest of the cycle.

From this energy model, we can see that the power consumption of the node that uses an appropriate communication protocol associated with a multiradio system (14.43mW) is reduced by approximately 15% compared to a node that works in a single radio system (16.83mW). This will translate to an increase in battery lifetime of 10-15% in a typical application (based on a standard AA battery).

VII. Conclusions & Future Work

Interoperability between communications protocols operating using different radio technologies is a major issue within the realm of wireless sensor technology where numerous wireless sensor technologies could be operating in the same vicinity. Middleware is one software solution that aims to overcome this problem. Middleware runs at either the gateway or cloud level and incorporates drivers for numerous protocols (ZigBee, Z-Wave and EnOcean for example).

This paper has shown how multi radio architectures and networks offer the possibility of increased interoperability and energy savings at a network and node level and thus are ideal for use in such HAN architectures. In addition, the multiradio architectures described address some of the issues associated with the fact that in the resource-constrained systems typically used in sensing systems for the built environment, energy is often the primary constraint and impacts on all aspects of the sensor system.

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. Aspects of this work have been funded by the European Union Horizon 2020 project MOEEBIUS under grant agreement 680517.

REFERENCES

[1] B. O'Flynn, M. De Donno, and W. Magnin, "Multiradio Sensing Systems for Home Area Networking and Building Management," The Fifth International Conference on Smart Cities, Systems, Devices and Technologies (SMART 2016), IARIA, May 2016, pp. 25-30, ISSN: 2308-3727, ISBN: 978-1-61208-4763.

[2] F. Zhao and L. Guibas, Wireless Sensor Networks: An Information Processing Approach, ISBN-9781558609143, Elsevier, Chapter 8, pp. 294, 2004.

[3] AUTHENTIC Webpage, http://www.creativedesign.ie/ierc_test/?homeareanetworks=AUTHENTIC-for-home-area-networks-han 2016.11.25

[4] K.Curran, Recent Advances in Ambient Intelligence and Context-Aware Computing, IGI global book series Advances in Computational Intelligence and Robotics (ACIR)(ISSN: 2327-0411), Chapter 10, pp. 155-169.

[5] IERC Website, http://www.ierc.ie/ 2016.11.25

[6] M. T. Delgado, H. Khaleel, C. Pastrone, and M. A. Spirito, "Underlying connectivity mechanisms for multi-radio wireless sensor and actuator networks," The 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob 2013), IEEE, Oct 2013, pp. 408-413.

[7] J. Ansari, X. Zhang, and P. Mahonen, "Multi-radio medium access control protocol for wireless sensor networks," Int. J. Sen. Networks, 8(1):47-61, 2010.

[8] B. Kusy et al., "Radio diversity for reliable communication in wsns," in Proc. Int. Symp. Inform. Process. Sensor Networks.,Chicago, IL, 2011, pp. 270–281.

[9] J. Buckley et al.,"A novel and miniaturized 433/868mhz multi-band wireless sensor platform for body sensor network applications," Ninth International Conference on Wearable and Implantable Body Sensor Networks (BSN 2012), May 2012,, pp. 63-66, ISBN: 978-0-7695-4698-8.

[10] L. Loizou, J. Buckley, and B. O'Flynn," Design and analysis of a dual-band inverted-f antenna with orthogonal frequency-controlled radiation planes," Antennas and Propagation, IEEE Transactions on, 61(8):3946-3951, 2013.

[11] L. Loizou, J. Buckley, B. O'Flynn, J. Barton, C. O'Mathuna, and E. Popovici," Design and measurement of a planar dual-band antenna for the Tyndall multiradio wireless sensing platform," In Sensors Applications Symposium (SAS 2013) IEEE, Feb 2013 pp. 11-14, ISBN: 978-1-4673-4636-8.

[12] R. Jurdak, C. V. Lopes, and P. Baldi, "A survey classification and comparative analysis of medium access control protocols for ad hoc networks." IEEE Commun. Survey. Tutorials, vol. 6, pp. 2–16, Jan. 2004.

[13] BTNode http://www.btnode.ethz.ch/ 2016.11.25

[14] Shimmer Mote link www.shimmer.com 2016.11.25

[15] http://www.libelium.com/products/waspmote/hardware 2016.11.25

[16] R. Jurdak, K. Klues, B. Kusy, C. Richter, K. Langendoen, and M. Brunig, "Opal. A multiradio platform for high throughput wireless sensor networks," Embedded Systems Letters, IEEE, 3(4):121-124, 2011.

[17] C. O'Mathuna, T. O'Donnell, R. Martinez-Catala, J. Rohan, and B. O'Flynn, "Energy Scavenging For Long-Term Deployable Wireless Sensor Networks," Talanta, 75 (3):613-623.

[18] D. Fuji, T. Yamakami, and K. Ishiguro, "A fast-boot method for embedded mobile Linux: Toward a single-digit user sensed boot time for full-featured commercial phones," Proc. - 25th IEEE Int. Conf. Adv. Inf. Netw. Appl. Work., (WAINA 2011), March 2011, pp. 81–85, ISBN 978-0-7695-4338-3.

[19] C. W. Chang, C. Y. Yang, Y. H. Chang, and T. W. Kuo, "Booting time minimization for real-time embedded systems with non-volatile memory," IEEE Trans. Comput., vol. 63, no. 4, pp. 847–859, 2014.