Innovative Low Power Multiradio Sensing and Control Device for Non-Intrusive Occupancy Monitoring

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Keywords: Smart Sensing, Low Power Consumption, Building Energy Management (BEM), Multiradio Systems, Multisensing Systems, Internet of Things.

Abstract: New tools and methodologies to reduce the gap between predicted and actual energy performances at the level of buildings and blocks of buildings are in continuous development in academic and industry organizations. The development of Wireless Sensor Networking (WSN) technology plays a core role in this field since their development enables the monitoring and control of application within the building environment. In this paper the development of a low power consumption multiradio and multisensing system to monitor building conditions and enable the interaction of occupants with devices through embedded actuators is described. The device (named NOD) incorporates a 32-bit ARM-Cortex microcontroller, a variety of sensors to monitor the ambient conditions – luminance, temperature, humidity, air quality - and multiple radio interfaces - WiFi/Bluetooth LE/868MHz. The NOD is intended to be used as a desktop device with a dedicated user interface. A description of the system and its features and functionalities is provided.

1 INTRODUCTION

With the increasing demand for more energy efficient buildings (Laustsen, 2008), the construction and energy services industries are faced with the challenge of ensuring that the energy performance and savings predicted during energy efficiency measures definition is actually achieved during operation. There is, however, significant evidence to suggest that buildings underperform. A, so called, "performance gap" which is attributed to a variety of causal factors related to both predicted and in-use performance, implying that predictions tend to be unrealistically low whilst actual energy performance is usually unnecessarily high (MOEEBIUS, 2016).

It is also important to monitor the air quality in offices environments and take actions to improve it. Poor indoor air quality can reduce the performance of office work by 6-9% and these negative effects on performance are accompanied by general symptoms such as headache and concentration (Wyon, 2004).

Wireless Sensor Network (WSN) systems are becoming an increasingly popular technology that is used today in a myriad of applications such as Building Energy Management (BEM), Smart Homes, Home Area Networking (HAN), smart cities and environmental monitoring applications.

New architectures are required to offer improved inter-operability, to improve the 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 of transmission and low data rate communication properties (O'Flynn, 2016). The use of a wireless sensing system reduces the total cost of the network installation compared to traditional wired sensing systems which ranges from 40 to $2000 per linear foot of wiring (Feng Zhao, Leonidas and Guibas, 2004).

The WSN group in TYNDALL is participating in "MOEEBIUS – Modelling Optimization of Energy Efficiency in Buildings for Urban Sustainability", a project funded by the European Union's Horizon 2020 research and innovation programme. MOEEBIUS introduces a Holistic Energy Performance Optimization Framework that enhances current

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(passive and active building elements) modelling approaches and delivers innovative simulation tools which deeply grasp and describe real-life building operation complexities in accurate simulation predictions that significantly reduce the "performance gap" and enhance multi-fold, continuous optimization of building energy performance as a means to further mitigate and reduce the identified "performance gap" in real-time or through retrofitting of appropriate sensing technology (Launsten, 2008).

To enable this, the MOEEBIUS NOD has been developed as a hardware device to monitor building context conditions and further enable the interaction of occupants with devices through embedded actuators.

Section 1 of this paper introduces the subject matter, the application space and the objective of this work within the project. Section 2 reports the state of the art in current wireless sensing system technologies for indoor air quality monitoring and multiradio platforms. Section 3 describes the "NOD" developed within the project. Section 4 describes the configuration and the operational mode of the device. Section 5 investigates power consumption characteristics of the platform. Section 6 concludes the work and outlines some directions for future work and research in this area.

2 PREVIOUS WORKS

A variety of wireless sensors systems are available and are continuously under development using different communication standards, proprietary and non-proprietary, such as ZigBee, IEEE 802.15x and Bluetooth. The use of one protocol instead of the other carries some advantages but also some disadvantages. Indoor range of transmission above the GHz frequency is quite limited especially for indoor applications with dense obstacles that will cause interference (Harwood, 2009). The Wi-Fi technology overcomes those issues by using 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 (O'Flynn, 2016).

A number of the currently available systems for indoor air quality are reported here as well as a selection of multiradio platform currently in use in such systems.

The "M-POD" (Jiang, 2011) is the portable IAQ sensing device wireless embedded sensing, computation, and communication device based on the Arduino BT (Figure 1.a). It is capable of sensing the concentrations of a number of air pollutants and either storing these data or transmitting them to nearby smartphones via its Bluetooth interface. The M-pod has a humidity sensor, light sensor, two temperature sensors – one upstream to measure ambient air temperature and the other downstream to measure the temperature near the sensors, a CO2 sensor, and low-cost metal oxide gas sensors. The battery lifespan is approximately 5.5 hours if an M-pod is continuously on and greater than 24 hours when in low-power mode.

The "AirSense" (Fang, 2011) is a IAQ sensing platform developed to use with the Arduino Uno Ethernet board. The platform has three onboard sensors including temperature, humidity and VOCs sensors (Figure 1.b) and is enclosed in a 3D printed case. The sampled sensor data are transmitted to the cloud server via the onboard Ethernet port. Besides the onboard sensors, AirSense also incorporates a standalone consumer-grade Particulate Matter (PM) sensor DC1700 from Dylos (AQMD, 2015) to measure the concentration of indoor PM 2.5.

The "Authentic" board (O'Flynn, 2016) (Figure 1.c) is a Multiradio Sensing Systems for Home Area Networking and Building Management based on a 32-bit microcontroller, incorporating temperature and light sensors and three radio modules (ZigBee/6LoWPAN, Bluetooth LE, 868MHz). 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 (O'Flynn, 2016). The system needs an external gateway in order to send the data to internet.

The BtNode V3 (BTNODE, 2007) (Figure 1.d) is a platform with two radios onboard. It incorporates a Chipcon CC1000 low power radio (433-915 MHz) and also has an additional ZV4002 Bluetooth radio (2.4 GHz).

The Wasp Mote (LIBELIUM, 2017) is a platform tha has separate 868 and 900MHz radio modular plug-in boards, but only a single radio module can be operated at a time and true multi-radio operation is not feasible.

The NOD device described in this publication can be also used as repeater increasing the range of the network. Moreover it offers the possibility to interact with the user through buttons and display or an Android Application for maintenance or data visualization.

Figure 1: Multiradio systems: a) M-POD b) AirSense c) Authentic board d) BtNode V3 e)Wasp Mote.

3 SYSTEM IMPLEMENTATION

The Nod is a desktop device which senses human presence, ambient temperature and humidity, air quality and light conditions in the user's vicinity and communicates these parameters wirelessly to a gateway. The Nod device also provides an intuitive and easy to use interface with feedback that allows a user to input and send commands to the Building management layer through a gateway to control the ambient environment in order to maximize user comfort. The latency (delay) is in the order of milliseconds and is not apparent to the user.

A specification process was undertaken with consortium partners from industry and academia to identify the core requirements associated with a wireless system for deployment in offices. Technical features which were 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.

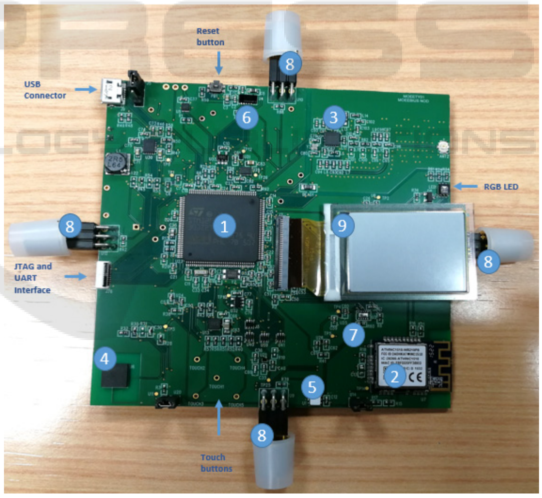

Figure 2: MOEEBIUS NOD Platform.

The platform described in the following sections of this paper is a novel low power consumption multiradio and multisensing system based on a 32-bit ARM-Cortex-M4 microcontroller, incorporating multiple radio interfaces - Bluetooth LE/868MHz/WiFi - to provide increased connectivity in deployment, and potentially reduce the interference impact on the network as the system can hop from ISM band to ISM band automatically. It also includes sensors for detecting human presence, ambient temperature, humidity, air quality and light conditions in the user's vicinity (~5m) in a 360° field of view.

The network of NOD devices adopts a standardized wireless mesh topology, architecture and information flow (to overcome deployment site obstacles, such as walls in indoor environments, and maximize communication reliability). The selection of the network topology takes into account the building types and installations and the maximum distance from the gateway.

The NOD can receive user inputs via an intuitive and easy to use interface. The users will be able to set control settings on the different device types (HVAC and lighting) and further receive information about the current status of each device through a custom designed user interface.

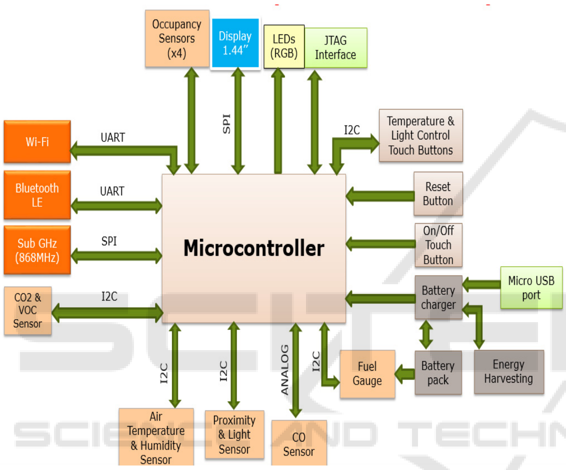

Figure 3: Block diagram of the NOD platform.

The final embedded system was designed around 10x10cm size (shown in Figure 3) and deployed in offices for preliminary tests and characterization. The main components of the NOD are the following.

Microcontroller: The heart of the system is the STM32F303ZET6, a 32-bit ARM Cortex M4 Core, 72MHz Maximum, 512KB flash, 64KB RAM, USB 2.0 (ST, 2016).

Sensors:

- Proximity and Light sensor (VCNL4020) (Vishay, 2014) interfaced to the microcontroller via I2C and which can detect proximity within 20cm. It is also able to sensing light level in the range 0.25lux – 16klux. It has also an interrupt function that will pull down the interrupt pin when the sensor detects the presence within the set threshold (20cm). This functionality will be used to activate the screen of the NOD when the device is in sleep mode.
- Temperature and Humidity sensor (Si7020) (Silicon Labs, 2016), the humidity and temperature sensors are factory-calibrated and the calibration data is stored in the on-chip non-volatile memory. This ensures that the sensors are fully interchangeable, with no recalibration or software changes required. The sensor is interfaced to the microcontroller via I2C.
- CO2 and VOC sensor (CCS811) (AMS, 2015), an ultra-low power digital gas sensor solution which integrates a metal oxide (MOX) gas sensor for monitoring indoor air quality (IAQ) including a wide range of Volatile Organic Compounds (VOCs) with a microcontroller unit (MCU), an Analog-to-Digital converter (ADC), and an I2C interface. The CCS811 supports multiple measurement modes that have been optimized for low-power consumption during an active sensor measurement and idle mode extending battery life.
- Occupancy sensor (EKMB1301111K) (Panasonic, 2016), a PIR motion sensor that guarantees an optimal detection capability and high reliability. The sensor is able to detect motion in 5m range with 94° of horizontal detection area and 82° of vertical. In order to have a 360° of coverage the solution adopted for the NOD is to use 4 sensors (one on each edge of the NOD device) to cover the entire range (Figure 4). When presence is detected the output of the sensor will be pulled high and it will cause an interrupt for the microcontroller.

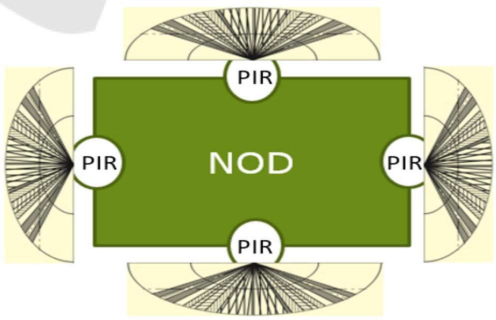

Figure 4: Solution adopted for presence detection.

Radio Communication: in operation the NOD will be part of a standardized wireless mesh network and, in order to send data to the middleware, the NOD needs to have at least one wireless communication module on board. As the NOD has more than one wireless module on board, when 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 to minimize retransmission and reduce power consumption.

- Bluetooth Low Energy (Cypress CYW20737S) (Cypress, 2017), enables the user to communicate with the NOD using a smartphone or tablet App. The module includes an embedded BLE antenna, 24 MHz clock, and 512 Kb EEPROM. The Bluetooth stack and several application profiles are built into the module.
- Wi-Fi (ATWINC1500-MR210PB) (Atmel, 2015), for interfacing the device to the middleware sending sensing data. It is a low-power consumption 802.11 b/g/n IoT (Internet of Things) module, which is specifically optimized for low power IoT applications with a fully integrated power amplifier, LNA, switch, power management, and PCB antenna. The embedded processor performs many of the MAC functions, including but not limited to: association, authentication, power management, security key management, and MSDU aggregation/de-aggregation. In addition, the processor provides flexibility for various modes of operation, such as STA and AP modes.
- Sub-1GHz radio chip at 868MHz (SPIRIT1) (St, 2016), enables the NOD as a multiradio platform. It is a very low power consumption device and the over the air data rate is programmable from 1 to 500 kbps. It can be used in systems with channel spacing of 12.5/25 kHz, complying with the EN 300 220 standard. The SPIRIT1 provides an optional automatic acknowledgement, retransmission, and timeout protocol engine in order to reduce overall system costs by handling all the high-speed link layer operations. It also supports an embedded CSMA/CA engine and An AES 128-bit encryption co-processor for secure data transfer.

Battery Management: the battery used is a rechargeable Lithium-ion Polymer battery with a capacity of 3000mAh, which is recharged through the USB port or through the use of energy harvesting systems compatible with the built environment connected to the battery charger chip (MP2617) (MPS, 2015). Onboard is also present a fuel gauge chip used to track the battery relative state of charge (SOC) continuously over widely varying charge and discharge conditions.

External Interface:

- Micro USB, used for multiple purposes. It is the power input for the board and for battery charging and it is also available for data transfer as it is connected on the on the interface of the microcontroller (USB 2.0).
- JTAG, to download the firmware into the microcontroller
  - UART, enable the NOD to communicate with external peripherals and it is also used for debugging purpose)

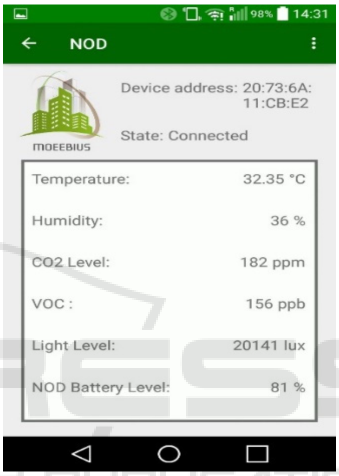

Figure 5: Moeebius NOD Android App.

User Interface: Electronic Paper Display (EPD), 1.44'', resolution of 128x96 (E1144CS021) (Pervasive Displays, 2016) and 5 capacitive touch buttons enable the human computer interface. The display gives a feedback to the user of the real time status of the NOD (battery level, connection status, sensors data). Touch buttons are used as inputs for setting different device types (HVAC and lighting). Another solution for the user interface can be adopted using a mobile app that will be able to connect to the NOD (via Bluetooth LE). It shows the NOD's status and is able to receive inputs from the user to set temperature and light level.

4 NOD CONFIGURATION AND OPERATING MODE

In this section is described how the NOD can be configured and the how it operates in the MOEEBIUS Network.

4.1 Configuration

In order to act as sensing device as part of a wireless network the NOD needs to be configured when it is powered on for the first time. This can be done through the Wi-Fi provisioning, a process of connecting a new Wi-Fi device (station) to a Wi-Fi network. The provisioning process involves loading the station with the network name (often referred to as SSID) and its security credentials.

Wi-Fi AP Provision mode primarily demonstrates how to configure the credentials (such as, SSID and Passphrase) in ATWINC1500 remotely. The configured credentials are used to connect with a desired access point.

Remote configuration facilities such as AP provisioning and HTTP provisioning modes are available. In HTTP provisioning mode, the HTTP page is used to configure the credentials. The HTTP server is running in the WINC firmware and the HTTP page is also stored in the WINC flash memory (Microchip, 2017).

The NOD starts as a SoftAP using open security mode (no security method) and broadcasts the beacon frames with SSID MOOEBIUS_PROVISION_AP_IDx (where Idx is the identifier of the NOD).

A smartphone or tablet can be used to connect to this AP. A web page will be opened where it is possible to set the SSID and password for the MOEEBIUS Network that the NOD will join. Those parameters are stored in the NOD so every time it is powered on it will connect to the network automatically.

Figure 6: Provisioning Web Page.

This procedure needs to be done for each NOD that will be part of the MOEEBIUS wireless network.

To save time and enable auto configuration this can be done only on one NOD device (master) and it will broadcast the information to the other NODs through the Sub1-GHz module.

Other modalities to configure the device could be through a smartphone/tablet App that send the configuration parameters (SSID and password of the wireless network) using the Bluetooth connection

4.2 Nod Operating Mode

As described in the previous section, when the NOD is powered up it needs to be configured (it has to be done only once) and the parameters (SSID and password) are stored in the flash memory of the Wi-Fi module. Then the NOD will scan for the Wi-Fi networks available and it will connect to the configured one; the NOD is connected to the Internet. Once the connection is established the NOD will configure the hardware driver (I2C, UART, SPI, ADC) in order communicate with the sensors and communication protocols on board.

By default the microcontroller is programmed to read sensors value (Temperature, Humidity, Light level CO2 and VOC) every 5 minutes. Duty cycle can be configured by the user through the BLE App or using the touch buttons. Another option is that the server can send a command to the NODs in order to change the time between two readings.

When the sensors data are available the NOD will create a packet with all the readings and it will be sent to the server in the JSON format using the HTTP REST API. Along with the sensor data and its reliability, the packet contains timestamp, country ID, building ID and point name. An example is the following:


```
[{
   "timestamp":"2017-02-
16T14:47:00+00:00",
   "countryid": "IE",
   "buildingid": "TY00",
   "pointname": "NOD01.CO2",
   "value": "400",
   "reliability":"1"
}]
```


Moreover all the sensors are shown on the display along with the battery level, connection status and current date and time.

To save power the NOD will enter in sleep mode after the packet is sent, then it will wake up after 5 minutes to read data from sensors and send them to the server.

When the NOD is in sleep mode, it can be woken up from different sources:

- Occupancy sensors: if presence is detected in the range of 5 meters the microcontroller will be woken up by the sensors interrupt and a packet containing occupancy information will be sent to the middleware.
- Touch button: if this button is touched by the user the system wakes up and it will be ready to receive user's inputs.
- Proximity interrupt: this is an alternative to the touch button, so if the user wants to wakes up the NOD, he has to put his hand close to the device (distance less than 20cm).
- Sub-1GHz: the NOD is a multiradio device and when it is in sleep mode and receives a packet from another device (that can be a command or configurations instruction) on the 868MHz ISM band the microcontroller will wake up and elaborate the information received.
- Fuel gauge: as described the NOD has a battery monitoring circuit that will send an interrupt to the microcontroller when the battery voltage is lower than a threshold in order to tell the user to charge the battery.

If the user wants to set desidered temperature and light level, he simply has to navigate into the menu and select the temperature or the light level. When the wanted level is reached (and displayed on the screen) the user needs to confirm the action. In this case a command is sent to the middleware in order to set the user's preferences regarding environmental conditions. The middleware will send back a confirmation that the action has been done.

5 POWER CONSUMPTION ANALYSIS

The current consumption analysis has been carried out for the normal operation of the NOD (after power up) that comprises the following behavior:

- Microcontroller, battery charger, fuel gauge and 4 occupancy sensors always ON
- Read sensors data one at time. After each sensor reading, it is set to standby mode
- Display sensors data on EPD
- Turn off EPD display
- Turn on Wi-fi and establish connection with the server
- Transmit data to the server
- Turn off Wi-fi
- Microcontroller goes into sleep mode for 5 minutes

Using the Agilent Technologies N6705B DC Power Analyzer, the current consumption for each of the main components of the NOD are reported in Table 1.

Figure 7 shows the NOD current consumption profile during the normal operational mode: power on, initialization, sensors readings and display, Wi-Fi transmission and sleep mode.

Table 1: NOD components current consumption.

NOD components	Current consumption
VCNL4020 (Light and Proximity sensor)	Standby = 0.02 mA Sensing = 0.45 mA
CCS811 (CO2/VOC sensor)	Standby = 0.05 mA Sensing = 29.5 mA
Si7020 (Temperature and Humidity sensor)	Standby = 0.01 mA Sensing = 0.2 mA
EKMC1600100 (occupancy sensors)	Sensing = 0.12 mA
STM32F302 (Microcontroller) and all sensors in stand by mode	ON (no operations) = 8.5 mA Sleep mode = 4.43 mA Stop mode = 2.96 mA Deep sleep mode = 2.69 mA
E144CS021 (EPD display)	Display on = 6.5 mA
ATWINC1510 (Wi-Fi)	Access point mode = 111 mA Transmitting = 110 mA

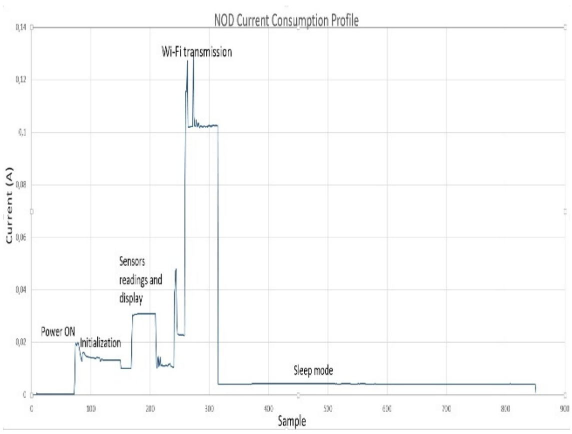

Figure 7: NOD current consumption profile (not to scale).

The average current consumption measured is ~6.23 mA.

A fully charged 3000 mAh rechargeable battery supplying the average current will last for approximately 20 days (1):

$$\text{No. of days} \quad = \frac{3000\,mAh}{6.23\,mA} * \frac{1}{24h} = \qquad (1)$$

This is an estimated value based on the presumption if the NOD is reading sensors data every 5 minutes configuring the sensors in the lowest power consumption mode, without any other interaction with the user (touch buttons and LEDs) or using the Bluetooth and sub-1Ghz features. Time for reading, display and transmission data are set at maximum values, so reducing them the current consumption will be less.

6 CONCLUSIONS/FUTURE WORK

This work describes the development and preliminary characterization of a novel low power consumption multiradio system for real-time indoor air quality monitoring incorporating three radio interfaces, WiFi, Bluetooth LE and 868MHz with all its features and operating modes that bring it to a sensing/ control Smart system (integrating a wide range of sensors and control interface) that is easy to install and configure. It also provides a solution for network congestion in environment such as Home Area Network and Commercial Buildings and Offices thanks to the embedded multiradio feature. Additional characterization and optimization of the system are currently underway and future work will be focused mostly on the firmware side improving the code adding the multiradio features using the sub-1GHz radio implementing protocols for reduced power consumption.

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