An Intelligent Home Automation Control System Based on A Novel Heat Pump and Wireless Sensor Networks

J. Brito, T. Gomes, J. Miranda, L. Monteiro*, J. Cabral, J. Mendes and J. L. Monteiro
Centro Algoritmi
University of Minho, Portugal

{jbrito, mr.gomes, jmiranda, jcabral, jose.mendes, joao.monteiro}@dei.uminho.pt, *leonel.monteiro@pintobrasil.pt

***Abstract*—One of technology's main goals is to providing comfort to humans. However, in order to be an aid, it has to be easy to install, use and maintain. The ever growing complexity of technological systems can only be achieved by converging different technologies. This is usually expressed as Cyber-Physical Systems (CPS), previews the symbiosis of several technologies in order to make them more accessible. This paper attempts to demonstrate the integration between two technologies such as: Heat-pump System and Wireless Sensor Network (WSN) to provide a new control mechanism for new building generations so-called smart houses. The proposed control architecture benefits from our developed WSN hardware platform. It enables the user to control and monitor the ventilation system using our developed mobile application and/or a personal computer. Also, the performance of the proposed hardware platform is measured in three different environments in order to observer the coverage area of the WSN.**

***Index Terms*—Wireless Sensor Networks (WSN), Home Automation, Integrated Home Control (IHC), Energy Efficiency, Indoor Air Quality (IAQ), Cyber-Physical Systems**

I. Introduction

In the last few years, interest in Wireless Sensor Networks (WSNs) has increased considerably in a large number of applications such as: habitat monitoring, health monitoring, precision agriculture, forest fire detection, water quality monitoring, infrastructural health monitoring (bridges, slopes, and roads) and home automation [1,2,3,4,5,6], among other areas. WSNs typically comprises many distributed autonomous sensor nodes, that have sensing unit boards, on-board processing and wireless communication capabilities [7].

These sensors have been effective employed to monitor various physical quantities, like temperature, pressure, flow rate, humidity, acoustics, vibrations, light and even pollution levels [8]. Due to the rapid growth of sensing and positioning technologies [9], the WSN has proven its potential to be a low power [10] viable solution for various low level monitoring and control applications.

Recently, Intelligent Buildings (IBs) have become one of the most popular research areas since the optimized usage of resources and energy conservation in the buildings is vital. The IB is a technology that employs integrated automated control systems in the buildings in order to control the energy usage and improve energy conservation. In the last few years, home automation has become popular due to the convenience, comfort and security that it provides to people. Some of the functionalities are light control, Heating, Ventilation and Air Conditioning systems (HVAC), water heating systems, appliances and other equipment that can be automated. People's awareness about energy consumption and environmental issues is increasing. This leads to the creation and optimization of renewable energy systems.

An automated building is a building in which the mechanical and electrical devices are monitored and controlled by intelligent, computerized electronic control systems. In such buildings, energy consumption of devices is optimized by automation demand-oriented control systems. To manage all the different devices, a comprehensive sensor and actuator network infrastructure is needed, that usually entails extensive and expensive wiring. One possible solution is the use of WSNs not only as sensory system but also as an intelligent controller.

In this paper, a novel heat-pump machine (air and water), capable of controlling and optimizing the air flow and the indoor air quality (IAQ) minimizing power consumption, is presented. It uses a new prototype heating system for water and air that combines on a single equipment air and water pumps, exploring simultaneously the benefits of the WSNs. The overall control system is based on a WSN where all the ventilation units, located inside rooms, are equipped and controlled by sensor nodes, in order to provide an energy efficient HVAC system. The system can also be remotely controlled using a mobile application installed on a smartphone, or through a web browser.

The remaining of the paper is structured as follows: on section II the overall system's architecture is discussed; section III presents the developed hardware; section IV the nodes software and the smartphone application; and section VI presents the conclusions of this work.

II. System Architecture

The Integrated Home Control (IHC) architecture and the overall system architecture are shown in Figure 1 and 2

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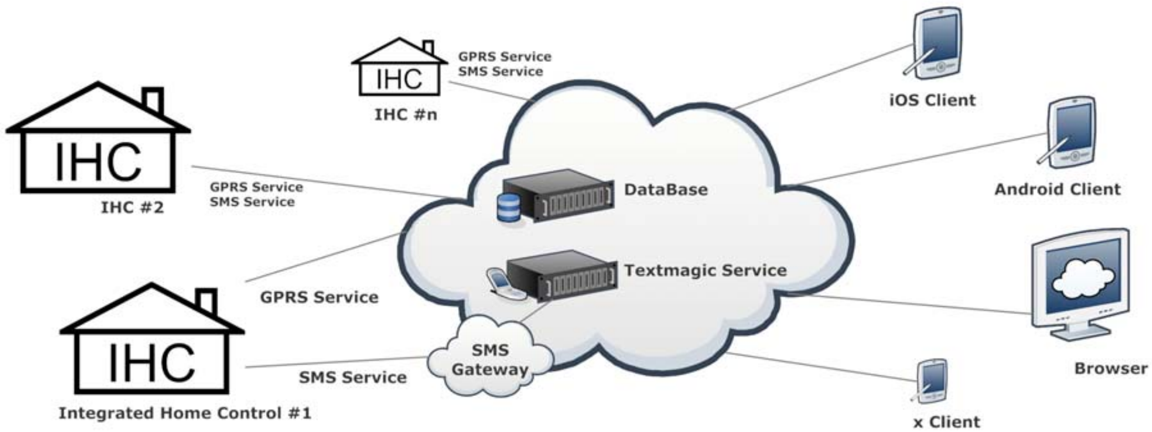


Figure 1: Overall system architecture

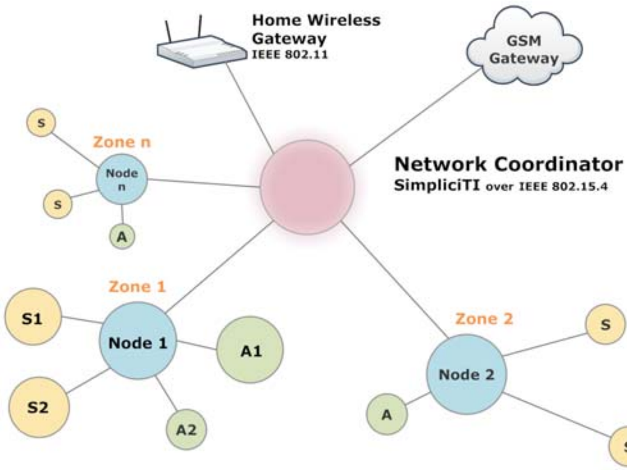


Figure 2: Integrated Home Control System

(a) Outdoor machine (b) Hybrid Heating Pump (c) Room/Zone ventilation System

Figure 3: Components of the proposed Heating Pump System

respectively. Every IHC has a GSM gateway that allows every user to control and configure the system remotely over two GSM services: General Packet Radio Service (GPRS) and Short Message Service (SMS). These services are presented on all available GSM generations, and therefore the system can be implemented in most of the countries in the world.

In both scenarios, the IHC gateway provides internet and remote connectivity to the client application. At this stage, for the SMS service, a web service provided by TextMagic [11] is used, that interfaces the IHC to the internet. The developed application clients may be installed on Apple's iOS or Google's Android. Additionally, a web browser interface is provided, allowing users to access and configure their own IHC system. All the information, like configuration, log activity or status is stored on a remote database and can be accessed by corresponding users. On the IHC side, users may also access and connect to system's control via the home network, without the need of using the GSM gateway.

Locally, the system consists of a WSN in a star topology and it uses the SimpliciTI Protocol Stack [12] from Texas Instruments over the standard IEEE 802.15.4 [13]. Despite using a simple network topology, this protocol stack provides devices to work as range extenders to increase network range up to 4 hops, making possible the full coverage of the building. Every room/zone has a network node equipped with sensors like presence detectors, temperature and/or humidity, along with actuators for controlling the ventilation system.

According to the temperature and/or humidity inside the room, network nodes may control the ventilation system (Figure 3c), in accordance with defined thresholds or user configured parameters. All the communications are made through and to the network coordinator, which controls the hybrid heating pump system (Figure3b). The communications between the mobile application and the coordinator are locally made using the home wireless network through the gateway connected to the coordinator. For the remote connections, the network coordinator uses the GSM gateway through GSM and/or GPRS. In case of wireless system's failure, local configurations are still possible, through a local wired control system.

III. Developed hardware

A. *Developed Sensor/Actuator Node Board (SAB)*

The SAB shown in Figure 4 is installed inside the ventilation system (Figure 3c).

The board is composed by sensors, actuators and communications boards. In this first prototype, the sensor board is

Figure 4: Sensor/Actuador Board (SAB)

Figure 5: Developed coordinator/gateway board (CGB)

equipped with a temperature and humidity sensor in order to gather data from the room where the ventilation system is installed. Other sensors can be easily installed enabling, for example, presence detection and water leakage detection. This board is connected to the actuator board, which is responsible to control (i.e. turn off, turn on, standby) the ventilation system.

The communications module consists of a System-on-Chip (SoC), CC2530 from Texas Instruments, and a PCB antenna that allows system to save space inside the ventilation equipment. An external antenna can be plugged in order to increase the coverage area of the system. The SoC is IEEE 802.15.4 compliant and operates on the 2.4GHz frequency. This modular design, with different boards, attached to each other instead of a single one, allows system to be dynamic and reusable, where different sensor boards or actuators may be used. Different communication modules with different SoCs, like CC1110 [14] from Texas Instruments, operating at the frequency of 868MHz with and without RF signal boost, may also be used according to the installation place requirements.

B. Coordinator/Gateway Node Board (CGB)

The CGB shown in Figure 5, is the network coordinator. It consists of the GSM gateway, the Home Wireless gateway and the communications board. This board is also connected to the heating-pump control board (Figure 6), in order to control the main heating-pump. The heating-pump board also provides power to the CGB so the last can be always-on to coordinate all the SABs.

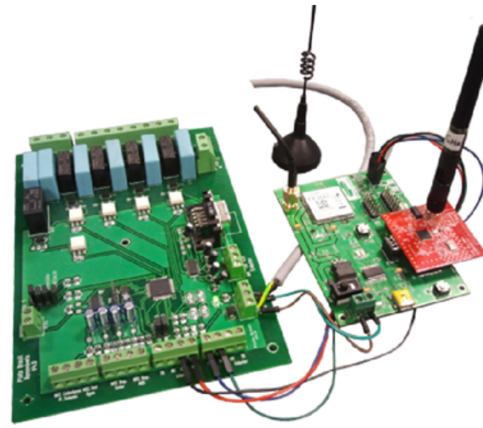


Figure 6: Integration between CGB and heating-pump board

The CGB is located on the heating-pump system (Figure 3b). This network node is responsible for receiving and sending messages from/to the SAB in order to control the ventilation system and to read the system status. To enable connectivity between remote application and the IHC, this board is equipped with a GSM gateway, which can communicate via SMS and/or GPRS, to allow remote clients to control the whole system.

Since the CGB is connected via IEEE 802.11 [15] with the Home Wireless Gateway Router, when users are near the IHC, they can control it by connecting the mobile equipment, running the mobile application to the home network, instead of using the GSM or GPRS services.

The communications module also has a SoC CC2530 from Texas Instruments, with a PCB antenna and a socket for optional external antenna. The two available frequencies, based on IEEE 802.15.4 [13], are 868MHz (CC1110) and 2.4GHz (CC2530) also with or without signal booster.

IV. System's Software

A. Mobile Application

In order to monitor and control the system, two mobile applications were developed, one for Apple's iOS and other Google's Android, providing the user the ability of monitoring and controlling the temperature and monitoring the humidity for a maximum of five zones as well as controlling a system calendar. Both applications can be interchangeably used for monitoring and controlling the system since the information of the system status is stored on the gateway node.

When the application starts, the screen on Figure 7a is displayed with the last known state of the system. On this screen, the user turn the system on/off, see the temperatures inside and outside the building, and command if the ventilation system must heat or cool the space. There is also the possibility

(a) Home Screen (b) Zone Control Screen

Figure 7: Developed iOS Application: screen examples

to individually monitor and control the temperatures of each of the five zones, using for that the screen represented on Figure 7b. On this screen, the individual temperature of a zone can be monitored and set, and also the humidity level is displayed. For each zone there is also the possibility to turn the ventilation system on or off.

On Figure 7a the current parameters of the system can be read from the CGB by pressing the "Read" button on the bottom of the screen. A SMS or GPRS message is sent to the CGB that replies with a SMS with the current state of the system. In order to get or set values, the user has to always explicitly request that from the application.

B. SAB Firmware

The SAB is responsible to control a ventilation system based on the values defined by a user. In order to do this, the node requests those from the gateway node in order to correctly actuate. The diagram of the Figure 8 represents the SAB operation. First, the microprocessor and the communications have to be correctly initialized, otherwise it stays on that state. After initialization, the node tries to create a link for communication with the CGB. If a connection was successful, the SAB starts acquiring temperature and humidity of the respective zone and send those values to the network coordinator. The coordinator replies to the message and sends the reference (threshold) values, that makes the node actuate on the ventilation system. If a network link is not created or communication is not established, the SAB will actuate on the ventilation system with the previous defined values. Those values may be default values, last received configured values, or manually set values.

C. CGB Firmware

The CGB manages several system modules, like GSM gateway, wireless network module and the interface with the heating-pump control board. These modules are sequentially initialized and then treated by the microcontroller. The activity diagram is shown in Figure 9.

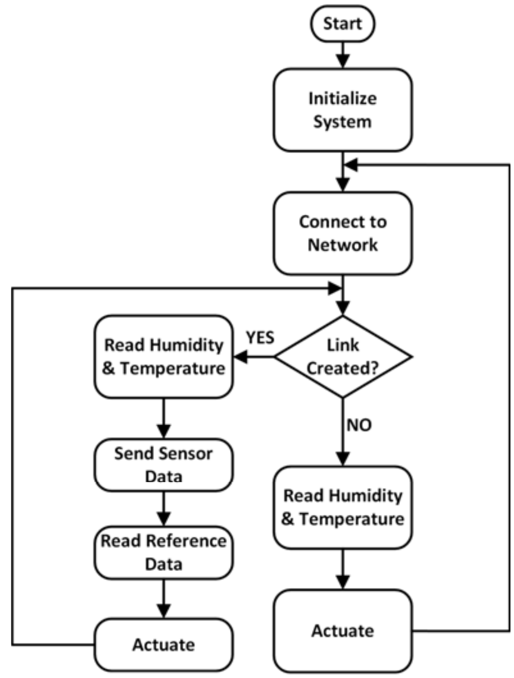


Figure 8: SAB software activity diagram

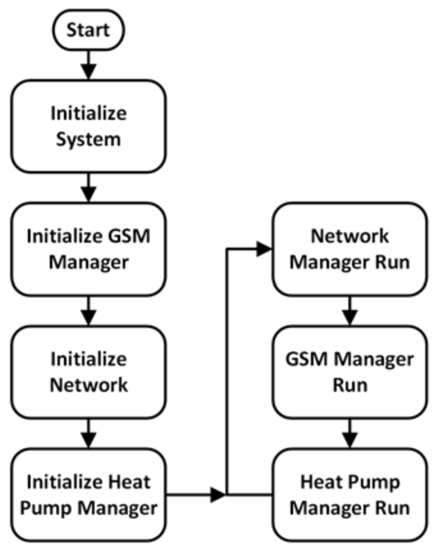


Figure 9: CGB software activity diagram.

After the SoC initialization, the node initializes the GSM gateway. The process starts with a module reset followed by the SIM card initialization. After that, the Hardware Control Flow feature is enabled, in order to control the serial communications between the CGB and the GSM gateway. To finish the initialization of the GSM gateway, the SMS and GPRS service are activated and configured. All the previous stored data like old SMS or settings are deleted and updated.

When the GSM gateway has been initialized, the CGB initializes the network module. This module consists of initializing all the wireless communications systems for local PAN (IEEE 802.15.4) and LAN (IEEE 802.11) networks. For the

Configuration	SAB Data	VS Control	CRC32

Figure 10: Message exchanged between CGB node and the heating-pump board.

local PAN, the network manager is initialized, enabling the node to receive and create links between the trusted SABs. A link between the Network Coordinator and the Home Wireless Gateway is also established.

In order to complete the initialization process, the heat-pump manager module is configured and started. It consists of a protocol message, exchanged by the heat-pump control board and the CGB, which is used to send and receive configuration and control commands of the whole system. When all the modules are initialized, the CGB keeps running in order to control the whole system.

D. WSN Communication Protocol

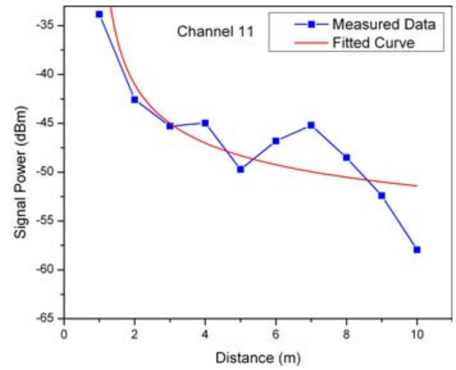
As mentioned before, the IHC system consists of a WSN in a star topology and it uses the SimpliciTI Protocol Stack over the standard IEEE 802.15.4. User's application messages are sent on the payload of the SimpliciTI protocol RF message.

The format of the application protocol message is shown in Figure 10. The packet is composed by a configuration, a data message, a ventilation system (VS) control and a CRC32 fields. The configuration field is used to configure parameters like interior and exterior temperature, the programming mode and the operation mode of the heating pump. The data message is composed by the temperature and humidity data collected by the SABs. VS Control field is used to control if the VS of each zone must be on or off. CRC32 field is used to control the message integrity.

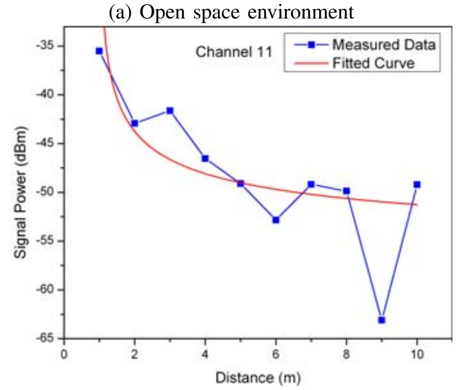
V. Tests and Results

For evaluating the proposed system regarding the RF coverage range, three different scenarios were used: open space, in building and industrial. The test consists in evaluating the Received Signal Strength Indication (RSSI) value for different distances between one ED and the AP. The transmit power of the ED is set to +4dBm and the IEEE 802.15.4 channel is set to the logical channel 11 (2405MHz). Despite the tests were on the channel 11, other channels may be used in order to avoid possible interferences with other surrounding wireless systems. Figure 11 depicts the obtained results from the performed tests.

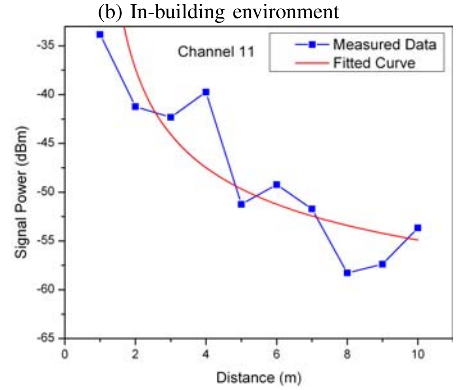
The results show better performance for the open space environment and the worst one for the industrial scenario. This is due the nonexistence of RF interferences on the selected radio channel by other RF devices on the open space scenario. As the system will be installed in an indoor environment, Figure 11b should be used as a reference. Results show that at 10m between ED and AP, the received RSSI value is around -77dBm. According to the RF transceiver sensitive in receiving mode (-88dBm with PER less than 1%), the distance between ED and AP can be at least 10m, and when the distance between both nodes is bigger with the Packet Error Rate (PER) over



(a) Open space environment



(b) In-building environment



(c) Industrial environment

Figure 11: Test scenarios

1%, one ED with range extender configuration should be used between.

VI. Conclusions and Future Work

In this paper, an intelligent heat-pump system for renewable and smart energy usage, the Eco-Smart Heat Pump, has been presented. It combines the Wireless Sensor Networks technology with a novel heat-pump machine, which uses air and water to control the humidity and temperature inside a room in order to control and optimize the air flow and the IAQ. It demonstrates that it is possible to integrate a heat-pump system with a WSN, providing a user to remotely control and monitor all the ventilation units located inside rooms, using mobile devices or a computer through a web browser, in order to provide an energy efficient home automation system.

All the network nodes (SAB and CGB boards) were developed by the authors, and the first system prototypes were already assessed at the heat-pump manufacture's facilities and were integrated with the heat-pump system that is already installed for testing purposes. The tests were carried out during two weeks, performing all the system's operation.

The results revealed a good system's performance, where two ventilation machines along with one heat-pump, were fully monitored and controlled, demonstrating that the usage of this system will contribute for a more smart energy usage, providing a more efficient and economic home automation system.

As a future work, the prototypes will be adapted for market production and more features will be added to the system, such as a gateway for integration with other home automation systems where standards like X10, or ZigBee may be supported. Another improvement to the system is to endow the network nodes with energy harvesting technics that can harvest the energy from the thermal difference produced by the ventilation system. Other ambient parameters may also be measured and other type of sensors may also be included to the system, like CO_2, CO, O_2, noise and luminosity sensors, in order to improve the control system based on the measured quantities.

At this stage the developed system relies on a third party service for the gateway between the GSM and internet service. To end this dependency a GSM server that can provide our own service is under development.

The first prototype uses a GSM modem compliant with the second generation (2G) of the GSM standard, but other modem interfaces can be used in order to take advantage of the new services offered by the newer generations (3G and 4G).

In order to increase the system's robustness, security and installation issues may be included. Using the AES protocol (existing peripheral on the SoC CC2530), messages exchanged between EDs and AP should be encrypted in order to secure the system against external intrusions and allowing the system to only communicate to authorized devices, registered during installation time.

Smart buildings of the future will integrate several embedded wireless equipment/devices based on the IEEE 802.15.4 standard. Also the coexistence with other wireless technologies is expected, such as IEEE 802.11 standard. For this reason, it is expected to have some systems to operate in the same frequency channel. In order to minimize wireless interferences with other coexistent systems, automatic channel selection will be implemented to the proposed system.

Also, this new monitoring and controlling heat-pump system may be expanded to work with other home equipment that are not yet being included and controlled by the other existing home automation systems.

VII. Acknowledgments

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