Design and Implementation of an Embedded Wireless System to Monitor a Hall-Effect Gas Sensor at a Household

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Abstract

The purpose of this work is to define and implement a proposal of a wireless system based on ZigBee modules to monitor the level of a stationary gas tank for a domestic household. It is intended to improve the transmission and information processing compared to similar monitoring systems that don´t use the ZigBee standard, to characterize and compare key performance elements.

1. Introduction

There is a growing demand on integrating a higher amount of information to domotic systems. It has been observed that some domestic devices do not have an adequate mechanism to incorporate their outputs to the main monitoring and control system, which is the foundation of an intelligent domestic home.

In this contribution, the process of transmission and data processing of the stationary gas tank of a domestic household is enhanced by using wireless transmission systems with ultra-low energy consumption. COP8 microcontrollers and MaxStream ZigBee modules were used for the system implementation.

In particular, the advantages and disadvantages of using the wireless Zigbee standard to transmit the measured gas level of a Hall effect sensor are drawn.

It was specifically analyzed the effect of distance and internal household obstacles (walls, ceilings) between the ZigBee transmitter and the receiver.

With this work, an implementation using ultra-low energy consumption (ZigBee, in this case) is presented.

Using Design of Experiments (DOE) techniques to define the required measurements and applying statistical analysis to the received wireless data, it was concluded that the effect of walls and ceilings on the ZigBee transmitted wireless data is negligible when MaxStream XBEE-Pro ZigBee modules are used.

2. Background

2.1. ZigBee Architecture

ZigBee is an open wireless standard based on IEEE 802.15.4 and published by the ZigBee Alliance.

It operates in the bands of 868 MHz (Europe), 915 MHz (Australia and USA) and 2.4 GHz (most countries). Transmission rate goes from 20 kbps (868 MHz band) to 40 kbps (915 MHz band) and 250 kbps (2.4 GHz band). ZigBee handles 16 channels with a coverage range from 10 to 70 mts (33-230 ft). It incorporates a full duplex access mechanism (both ways communication), which helps to prevent errors within mesh networks. ZigBee also implements security schemes during transmission and it is able to interact with many types of sensors [1], [2].

The Zigbee Architecture supports three main types of devices: coordinator, router and end device as shown on Figure 1 [3].

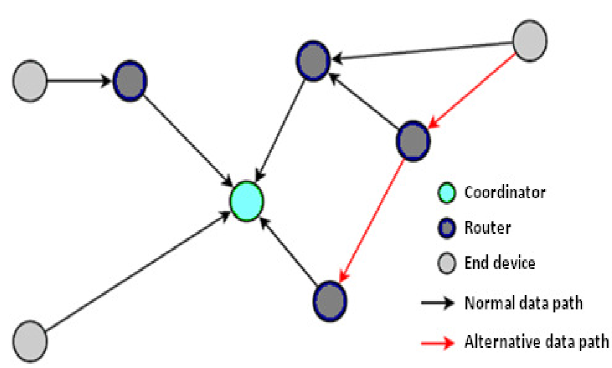

Fig 1. ZigBee architecture for a mesh network [3]

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The implementation of this system could be carried out with other wireless technologies. However, the main contribution of this work is that for residential systems, the ultra-low consumption of ZigBee makes it feasible and cost-effective to implement. The disadvantage of ZigBee may be the lower transmission rate [1].

Nevertheless, the amount of data to be transmitted for this application is not considerable and it is not required to update the level on real-time. Thus, the transmission rate is not an issue for this design.

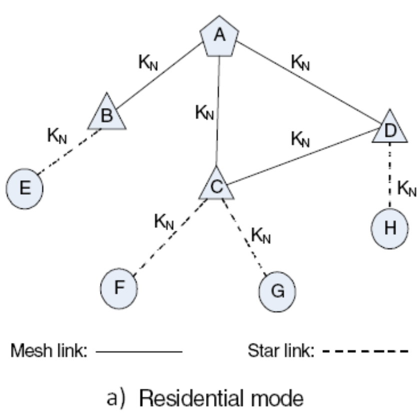
2.2. Security on ZigBee Architecture

ZigBee uses a symmetrical cryptography scheme that implements an AES 128-bit algorithm to offer security during data transmission. Additionally, ZigBee implements a freshness counter to prevent repetition attacks and integrity message checks to prevent their modification. Zigbee does not provide capabilities to verify digital signature. Nevertheless, with the use of cryptography, authentication schemes can be implemented [4].

In the ZigBee's security scheme, three types of security keywords are used: master key, connection key and network key.

A master key is a long time security key between two devices, which can be registered manually and can be sent wirelessly. It is used to send packages over the network and to send the encrypted connection keys. A connection key provides security during information exchange among two devices, while a network key provides overall network security. Both connection and network keys can be updated periodically [4]

ZigBee trust center manages the network members and the distribution of the security keys. It operates in two modes: residential and commercial. The number of keys is shown in Figure 2 for both modes, thus illustrating the simplicity of the residential mode used for this contribution.



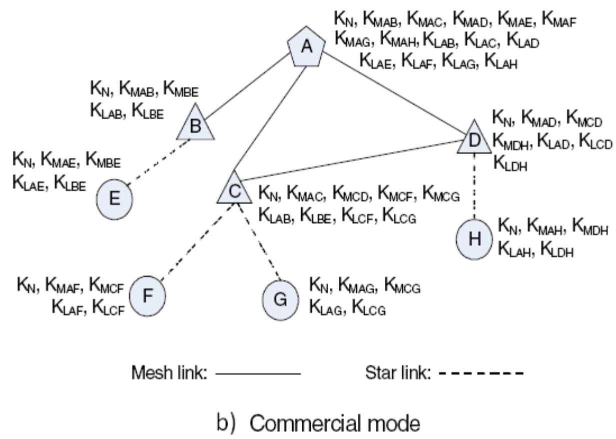


Fig 2. ZigBee Encryption keys for a) residential and b) commercial modes. [4]

As it can be observed from Figure 2, the residential mode uses only a single Network encryption key called KN, which is used for all the network devices.

3. Design and Implementation

3.1. Stationary LP Gas Containers

The stationary tanks for liquid propane gas (LP Gas) are specially designed steel containers used to keep the gas at high pressures.

In Mexico, the stationary container keeps a mixture of propane and butane gas (C_4H_{10}). In this container the liquid LP gas is located in the bottom part, whilst the vaporized gas floats in the top part as is shown on Figure 3 [5].

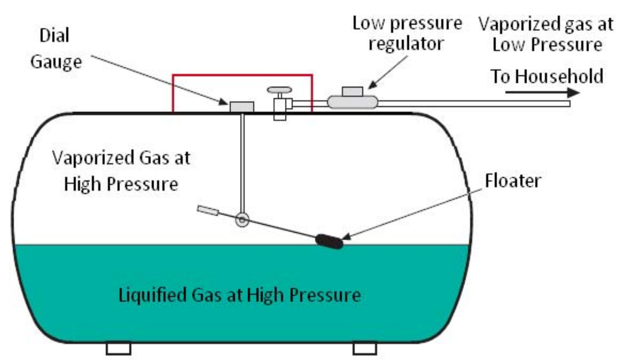


Fig 3. LP Gas container for domestic use. [5]

Every stationary container has a floating device that rests over the liquid gas level. The floater's rod can vary in size according to the diameter of the container.

The gears must be in the middle of the gas container. Also the gearbox is used to change the direction of the floater and it is attached to an aluminum tube. At the other end of the tube there is a magnet positioned just below the gas meter [5].

The dial gauge displaying the remaining tank capacity percentage is screwed to the exterior side of the container. The actual quantity of the liquid gas inside the container is indicated by a metallic arrow.

Figure 4 shows the internal mechanism of a floating device for a LP Gas container [5]

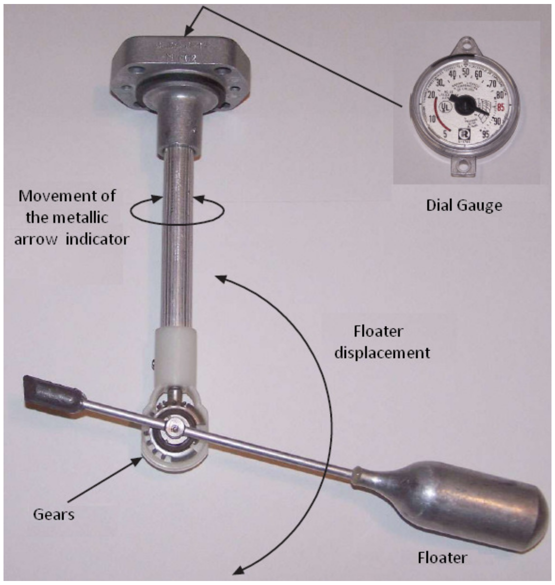


Fig 4. Internal Mechanism of a floating device for LP Gas container [5]

3.2. Hall Effect Sensor

Hall effect is a solid state technology that does not use mobile contacts. The magnetic connection is more trustworthy than systems depending on variable resistors. The Hall Effect sensors work by deviating an electronic flux that moves along a semiconductor. This deviation can be detected and converted into a ratiometric output voltage, proportional to the level of liquid gas inside the container [6].

3.3. Design Considerations

For the development of this monitoring system, the following considerations must be covered:

- A stationary container with a maximum capacity of about 300 liters.
- Due to the flammable environment of the LP gas container, the monitoring systems must be hermetically sealed and electrically shielded.
- The system must not need frequent maintenance and the battery supplies must last a considerable amount of time (two years, at least)
- The transmitted measured level does not require to be updated on a short basis, nor it requires high speed transmission rates.
- The transmitted information must incorporate security schemes to prevent hacking.

3.4. System Implementation

Based on the considerations mentioned in section 3.2, the following system is proposed:

- The system consists of two parts: one for the transmission in order to generate the level readings and be able to transmit them, the other part, a receiver to accurately receive the data and display the readings of the LP gas level.
- The system uses a device with a Hall-effect sensor and a ratiometric voltage output, due to its simplicity and reliability.
- The system converts the voltage using an analogical-digital conversion (ADC) of 8 bit, which gives a 0.4% resolution per sample.
- The system's core is based on a 8 bit microcontroller to process data and control the wireless transmission of the gas LP level.
- For the reasons provided in sections 2.1 and 2.2, ZigBee modules were used for wireless data transmission.
- The system displays the information received from the LP gas container in a LCD, updating the readings to configurable intervals.
- In order to save energy, the system must be in sleeping mode most time, reading data only every two hours and generating the correct data.
- The system's architecture is implemented so that other nodes can be implemented afterwards to construct a sensor's network for a better and more robust system for other domestic needs.

Figure 5 shows the block diagram of the proposed system.

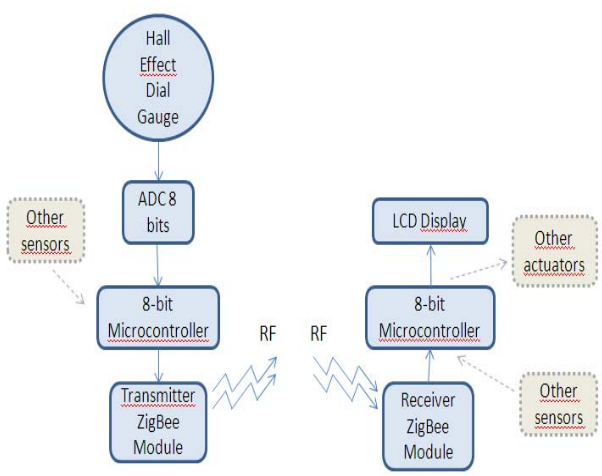


Fig 5. Block diagram of the proposed monitoring system

To choose the specific components of the system, simplicity was paramount. The components were selected according to their commercial availability and ease of program or configuration.

The Hall effect gas sensor should not be energized continuously or an output voltage variation will occur due to temperature compensation inside the sensor. The energization should last only a few milliseconds to generate the required radiometric output voltage [7]. The scheme implemented for this purpose uses a relay.

The 8 bit microcontroller chosen for the transmitter circuit was the National COP8SAA720N9, with 1KB OTP, 64KB RAM at 10MHz and 16 pins for input and output. It is energized using 5 VDC and does not require any external components to operate. It was chosen due to their ease of program, large instruction set, low EMI (Electromagnetic Interference) and robustness.

For the receiver it was chosen a National COP8SGR728N8 microcontroller, with 32KB OTP, 512KB RAM, 15MHz and 24 input / output pins, which are enough to implement a control and display center that could optionally incorporate signals from other sensors.

The architecture for the COP8 microcontroller is shown on Figure 6 [8-9].

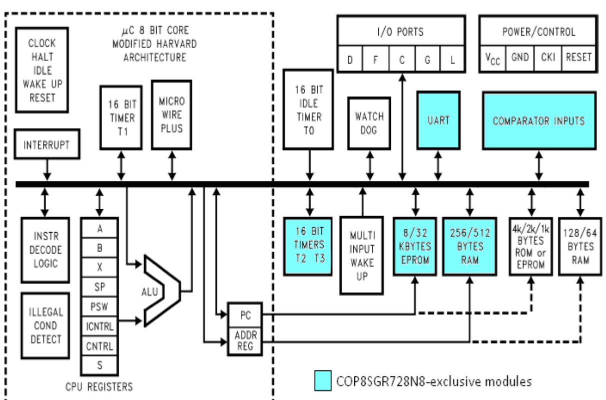


Fig 6. COP8 microcontroller architecture [8], [9]

The 8 bit serial ADC used was the National ADC0831C, whilst the LCD display used was a 2x16 Digitron SC162A3 with backlight.

The XBEE modules are small and simple to connect and use. They do not require external components and the communication with the microcontroller is by UART. A 9600 bps rate was chosen which allows sending data in a reliable way [10].

The ZigBee modules used were the Digi XBEE-Pro XBP24-BWIT-004 with wire whip, which transmits in the 2.4 GHz band at a rate of 250kbps with an output power of 63mW. It requires 3.3V to operate [10].

An important aspect to consider in the selection of the ZigBee module is the type of antenna used, since that can affect the message reception depending on the physical orientation of the transmitter and the receiver. Whip antenna was chosen since its toroidal radiation pattern helps to overcome this issue, as it can be observed in Figure 7 [11].

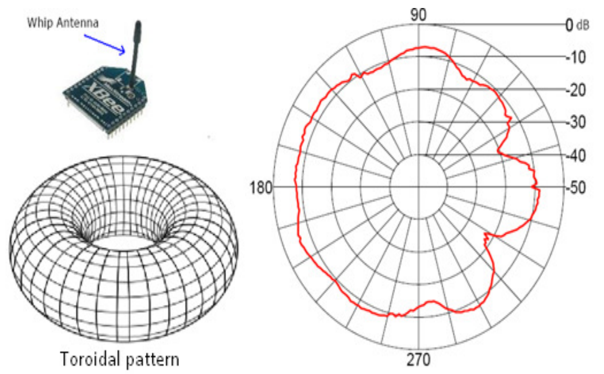


Fig 7. XBEE whip antenna radiation pattern [11]

The PCB prototype for the Transmitter and the receiver are shown in Figures 8 and 9, respectively.

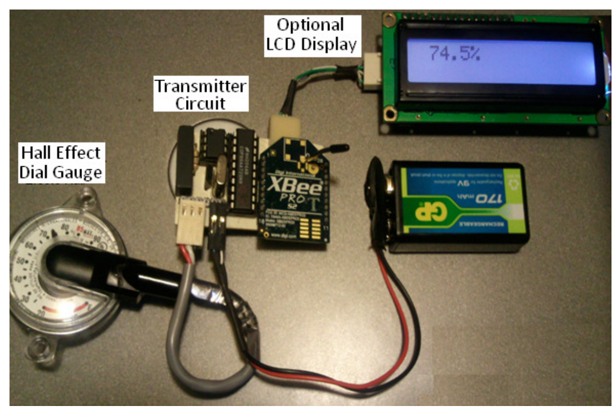


Fig 8. Design of the prototype for the transmitter

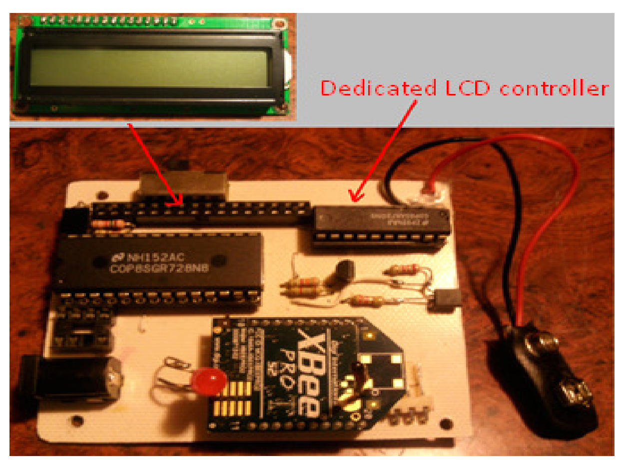


Fig 9. Design of the prototype for the receiver

The tasks that the embedded software in the transmitter's microcontroller carried out are shown in the block diagram of Figure 10.

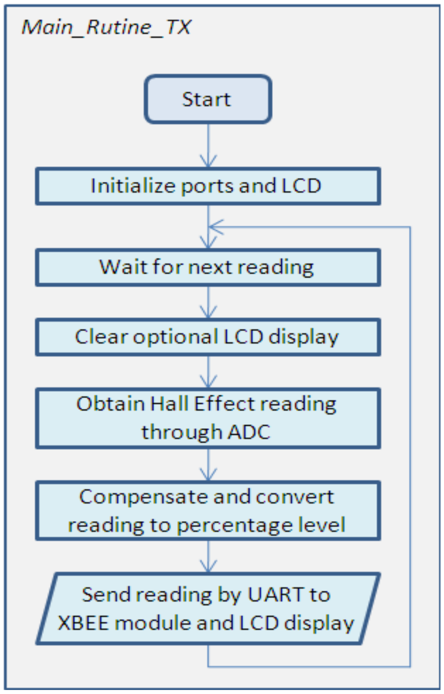


Fig 10. Block Diagram of the embedded software in the transmitter's microcontroller

The UART readings measured with a logic analyzer at the receiver's microcontroller confirmed that the transmitted bytes are properly received. This can be observed in the logic analyzer snapshot of Figure 11.

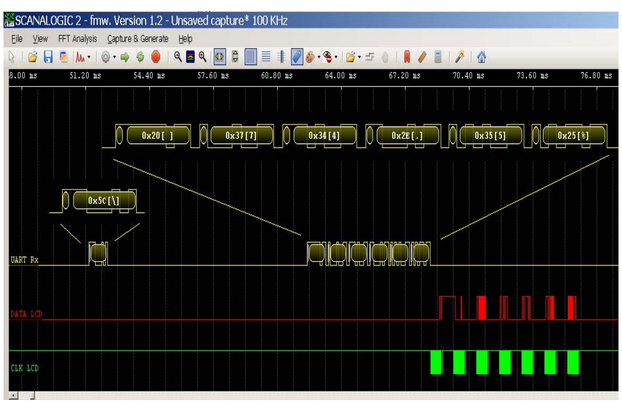


Fig 11. UART decoding of the received bytes at the receiver's microcontroller

3.5. Performance measurements

It was performed a pilot study in order to characterize the proposed system performance, by analyzing the effect of identified key variables on the successful reception of LP tank level readings.

The identified key variables are:

- Distance between transmitter and receiver. 4 observation levels (4 m, 8 m, 12 m, 16 m).
- Number of walls/ceilings between transmitter and receiver. 3 observation levels (0, 2, 4).
- The response variable selected is the standard deviation of time between successful messages received in a 63 sec period (because that was the buffer of the logic analyzer used).

The experiment was replicated 2 times.

4. Results

The resulting data from the pilot study is shown in Table 1.

Distance (m)	Walls/ Ceilings	Std Dev between readings	
		Reading 1 (ms)	Reading 2 (ms)
8	2	9.86	12.32
4	4	28.90	11.02
12	4	3.52	8.59
12	2	12.77	9.12
12	0	7.24	8.74
4	2	114.73	8.62
8	0	9.06	8.75
16	2	3.63	9.32
16	4	67.76	12.35
8	4	8.70	10.75
4	0	8.67	9.53
16	0	3.46	11.12

Table 1. Resulting data from the pilot study

In Figures 12 and 13 below it can be observed the analysis of the data obtained from the pilot study.

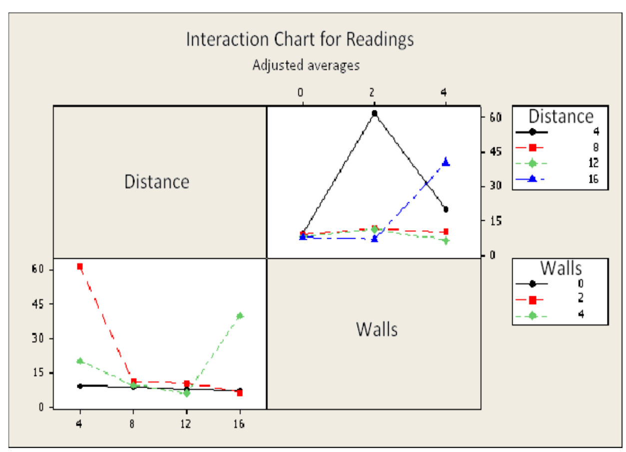


Fig 12. Interaction chart for measured readings

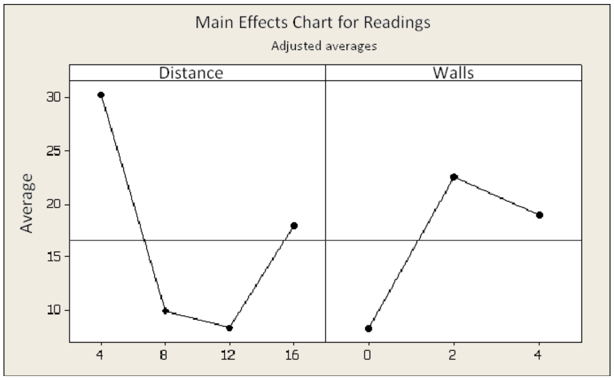


Fig 13. Main Effects chart for measured readings

When the number of walls/ceilings increases, it also increases the average reception time of the sent messages. This effect occurs as well when the distance between the transmitter and the receiver increases. This can be observed in the interaction plot in Figure 12.

In the main effects plot from Figure 13, it can be also observed a similar pattern, where the average reception time (based on Table 1 readings) increases as the distance or number of walls increases. There were 4 abnormal readings that caused an unexpectedly high average when the distance was 4m, and also when the number of walls was 2. This could be explained by a transitory interference that caused those readings to be lost. This makes the standard deviation measurement to be extremely high, causing the average increase.

From the pilot study results it can be observed that even when there is an effect of distance and number of walls in the detection time of the received messages, the data received kept its integrity, and the link between the ZigBee *coordinator* (receiver) and the *end device* (transmitter) was never lost in any section of the household.

5. Conclusions and Future Work

Based on the results obtained in section 3.5, it can be concluded that using a ZigBee-based wireless system to monitor the level of a household LP gas tank offers multiple advantages compared to a traditional wired system:

- Flexibility to place the receiver/display in any location within the household.
- Ease of installation. No wiring or complex synchronization sequence required.
- Feasibility to integrate the system as a new node of a sensor network for a domotic system..
- Possibility to acquire and transmit more signals using the same Zigbee module.
- Improved information security, since ZigBee standard controls network formation, implements an encryption algorithm and custom protocols can be implemented at the application level to manage/decode received data.
- Reliability on data reception, confirmed by the experiments performed in section 3.5

As future activities it is proposed the following:

- Design additional household data acquisition modules to be integrated directly with the main data processing module.
- Implement remote system configuration / monitoring from a PC or SmartPhone.
- Design a solar cell and rechargeable battery scheme to improve system's autonomy.
- Redesign the hardware to use newer electronic components to reduce energy consumption.
- Integrate the functionality of the Hall effect sensor, relay, microcontroller, battery and ZigBee module into a single dial gauge that can be placed directly on the LP gas tank, replacing the mechanical dial gauges currently available.

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