# Intelligent Containers based on a Low-Power Sensor Network and a Non-Invasive Acquisition System for Management and Tracking of Goods

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***Abstract*— This paper presents a prototype of a system for intermodal freight transport with electronics management of goods. The system is based on low-power wireless networks connecting intelligent containers. The proposed intelligent container can be configured with different type of sensors inside. With the objective to preserve the sealing of the container, data collected inside the container are transmitted through a metal communication channel based on ultrasonic techniques. Outside the container, the implemented system is composed by a long range and low power scalable wireless network. Finally, a management subsystem has been designed for tracking, monitoring and alarm reporting.**

***Index Terms*—Intelligent Containers, Intermodal Transport, Metallic Barriers, Piezoelectric Transducers, Tracking, Ultrasonic Communication, Wireless Sensor Networks**

## I. Introduction

Nowadays, almost 90% of the world trade is carried by cargo containers using different means of transportation, including railways, air, trucks and ships [1], making a huge impact on global economy. For example, transport sector generates around 7% of the European GDP (Gross Domestic Product) and almost 5% employment in the European Union [2]. Particularly, maritime transport means the most dominant mode of freight transport, with over 16 million containers in transit through the world daily [1]. Another example is the fact that 6 out of 10 main cities in the world have a port dedicated to freight transactions [3], providing a high impact over their economies.

Therefore, there is a trend to continuously improve the efficiency of this sector in ports and terminals, by the implementation of "intelligent containers". An "intelligent container" will allow interconnectivity between actors and activities in the intermodal freight system and the logistics network via wireless communication and sensing capabilities. Moreover, an "intelligent container" does not only measure and transmit the information, but also makes decisions locally to enhance the operational performance and minimize the amount of data to be transmitted [4].

In order to meet environmental challenges and mobility requirements, the European Union has developed a strategy to support the advance of sustainable transport systems, promoting intermodal transport instead unimodal transport. The objective is to contribute to real time traffic management, reducing delivery times and freight transport congestion [5].

Additionally, intermodal transport has many technical challenges about security and monitoring of goods. According to the Container Tracking and Security Market 2012-2022 analysis [6], the necessity of ensure the security of the freight assets will see an exponential growth in the next six years. Therefore, detection of terrorists threats, freight thefts and intrusions, contra-band materials, explosives and biological weapon threats, added to the real-time monitoring and status and damage reporting of goods, will need innovative mechanisms. They will allow a secure and efficient transport, providing services that benefit all elements of the logistics chain: exporters, authorities, shipping companies, port operators, importers and customers.

Moreover, the design of a wireless system for tracking and monitoring of goods faces some additional challenges, such as the long life container tracking requirement, the need for a non-invasive inspection, and a harsh environment for wireless communication, such as scenarios based on stacked metallic containers.

This paper presents a complete system, experimentally tested, to improve tracking, security and management of goods in intermodal freight transportation. As it will be detailed in Section III, the proposed system is composed by the sensors inside the container, ultrasonic communication to extract information from the container, a wireless network and dedicated software to manage the information.

The paper is organized as follows. Section II presents a study of the state of art of systems for monitoring, management and tracking of goods, comparing advantages and drawbacks of different technologies, commercial products and research works. Section III describes an overview of the implemented system, detailing each part or subsystem in Section IV. Section V is dedicated to describe some

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implementation aspects. In Section VI, experimental results and validation in a real scenario are presented. Finally, the conclusions are drawn in Section VII.

## II. Related Works

Intelligent transportation systems, with tracking and monitoring purposes, have been the subject of very active research in recent years.

About tracking functionalities, most of systems are based on RFID technology [7]-[8] because of its cost and ease of deployment. However, there are some important drawbacks such as collision problems, which are increased for applications with many stacked containers. Moreover, RFID technology is not efficient for location purposes [9]. Besides, RFID is sensitive to electromagnetic propagation issues in harsh environment, such as stacked metallic containers. Finally, there is a possibility of activating explosives inside the containers by using RFID.

Another popular tracking technique is based on Optical Character Recognition (OCR) because of its low start-up, repair and maintenance cost. However, OCR is a more complex and error-prone process, due to some reasons as damaged characters, different container surfaces, manufacture-dependent font colors and shapes, and need for LOS (Line-Of-Sight) [10].

The idea of an intelligent container with multiple sensors connected by a wireless network is not new. In 2002, [11] demonstrated the need to automatize the containers terminals in order to reduce the costs and increase its efficiency. Likewise, [3] proposes a low power wireless sensor network at 2.4 GHz, with tracking and monitoring purposes. However, this work was only implemented at simulation level. Furthermore, like other published solutions, to transmit the collected information to outside the container, it is necessary to drill it.

Other research work with integrated tracking and monitoring of goods functionalities is [8], with door-opening sensors only working during loading/unloading process. Most recent works have been focused on optimizing location and tracking functionalities for roads [12], railways [13] and maritime and seaports [14] environments, by proposing novel logistics algorithms, but without being integrated in a complete solution for monitoring purposes.

If we consider commercial products instead of academic researches, there are several proprietary solutions for tracking of goods and monitoring applications:

- Globe Tracker, based on WiFi transmission, which monitors only motion variables [15].
- Triton, based on GPS/GPRS to provide the location and temperature [16].
- TREC, based on GSM and ZigBee with tracking purposes [17].
- WiFi Smart Chip Tags (WFSCT), providing real time container identification, temperature monitoring, and hazardous and explosive material detection [18].

In general, most of these systems have several common features:

- Tracking is partially based on Global Positioning System (GPS), increasing the power consumption, or via satellite, requiring a Subscriber Identity Module (SIM card) per container.
- Limited to only 2-3 sensors variables, generally, only temperature and doors state.
- Wireless band at 2.4 GHz, resulting in more communication problems for high density of containers, which is the usual situation for cargo freight applications.
- Invasive systems, due to the need to drill the container to read the sensor variables. Additionally, this wired communication means a higher complexity in the installation and maintenance processes.

In the following sections a novel solution will be proposed in order to improve the limitations of the current systems:

- Six different variables are monitored: acceleration, temperature, humidity, state of the door (open/close), luminosity and movement.
- Low power wireless network at 868/915 MHz for tracking and monitoring purposes is implemented.
- Ultrasound based communication through a metallic channel is implemented, avoiding drilling the container or squeezing a cable through the door seal, so that preserving the sealing of the container.

## III. System Overview

As discussed above, this paper proposes a complete-solution for tracking and monitoring of cargo containers and goods, avoiding damage to the containers. The integrated system is composed by five main parts, which can be identified in Figure 1.

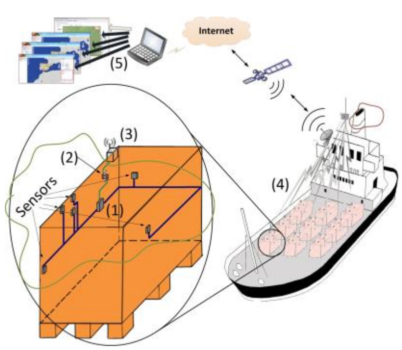


Figure 1. System Overview

1. Acquisition platform, composed by the sensor network and the sensor handler: collects the data inside the containers.
2. Non-invasive ultrasonic communication channel: transmits the information from inside to outside the container through its metallic wall.
3. Transponder controller: transmits the information from the ultrasonic receiver to the wireless

network on a harsh environment.

4. Wireless network: transmits the information between the containers and the internet-gateway.
5. A database and web server: receive the information of the cargo container in order to be presented to the final user. It will be used for tracking, monitoring and alarm reporting purposes. This subsystem will provide the service to the actors of the logistic chain.

The proposed system has to meet several requirements:

- Ranges of temperature (-25/75ºC) and humidity (0/100%) for terrestrial and maritime environments.
- Protection features: IP 67.
- Memory size and data codification so that all useful data of an entire trip is stored. This is necessary in case of loss of communication.
- Optimization of the available space reducing the size of the boards, cables and connectors.
- Very low power consumption.
- Easy installation: non-invasive communication and portable devices.
- Cost factor: design, manufacturing and maintenance costs must be irrelevant compared with the container and shipment costs.

In order to meet these requirements, the following decisions have been adopted:

- Selection of radio frequency: a wireless band feasible on harsh environments, with worldwide compatibility and high information bandwidth has been selected: 868/915 MHz (IEEE 802.15.4).
- Selection of ultrasound carrier frequency as low as possible (40 KHz) in order to reduce the attenuation through the metallic channel, avoiding multi-path effects and the use of complex equalization techniques.
- Selection of modulation scheme for the ultrasound communication: DBPSK (*Differential Binary Shift Keyed*) due its simplicity, robustness and no-coherent demodulation, reducing the complexity in the receiver side.
- Energy optimization:
    - To reduce costs, NiMH batteries powered a first prototype. However, at extreme temperatures, voltage output dropped. Thus, Lithium batteries were selected because they can stand better at lower temperatures.
    - Selection of the IEEE 802.15.4 standard, orientated to low power and efficient sensor networks.
- Security: need of key establishment, authentication, privacy and secure data aggregation by using the Authentication Encryption Standard AES 128.

## IV. Implemented System

### A. Acquisition Board

This module is installed inside the containers to monitor conditions of the traveling goods. It implements the interfaces with sensors, and performs data collection, local processing and temporary storage.

The acquisition board is made of:

1. A low power consumption 32bit-ARM Cortex-M3 central microprocessor STM32F103RD.
2. A CC2D33 temperature and humidity sensor.
3. A MAX44000 brightness sensor.
4. A HGDEST021B magnetic sensor.
5. A EKMB1203111 motion sensor.
6. A LIS3DSHTR accelerometer.

By using these sensors, the system is able to monitor temperature, humidity and luminosity, and generate real time doors, motion, shocks and freefall alarms. The acquisition board is powered by 3.6V Lithium batteries. The main features of these components are detailed in Tables I and II.

TABLE I
Acquisition Board: Microprocessor Features

| | |
|---|---|
| Current Supply Run Mode (All Peripherals Enabled) | 37mA |
| Current Supply Standby | 3uA |
| Clock | Up to 72MHz |
| DAC | 2 x 12Bit |
| ADC | 16 Channels x 12Bit |
| Flash | 384 KB |
| RAM | 64 KB |
| Interfaces | 2 x I2C, 3 x SPI, 2 x I2S, CAN, 3 x USART, 2 x UART, 8 x Timers (16bit) |

TABLE II
Acquisition Board: Sensors Features

| | Current Supply | Accuracy | Range | Interface |
|---|---|---|---|---|
| C2D33 | 750uA | ±2%RH, ±0.3ºC | 0 to 100% RH, -40 to 125ºC | I2C |
| MAX44000 | 5uA | 0.03Lux | 0-65535Lux | I2C |
| HGDEST021B | 3uA | 2mT | - | GPIO |
| EKMB1203111 | 2uA | - | 12m | GPIO |
| LIS3DSHTR | 11uA | 0.06mg/LSB (FS ±2g) | ±2g - ±16g | I2C |

Some of these sensor data (temperature, humidity and brightness) are collected periodically, while others are generated and collected by events, such as opening/closing doors, or movement of people inside the containers. Once the data are collected by the microprocessor, they are framed, modulated and transmitted by using the Digital-to-Analog Converter (DAC) of the microcontroller, as it will be detailed in the following section.

### B. Ultrasonic Front-End

With the objective to preserve the sealing of the containers, an ultrasonic communication through the metallic walls is proposed. Researches in ultrasound communication are very popular in many industrial and military applications, where the structural integrity has to be preserved, and metallic walls compromise the effectiveness of wireless communication. For example, ultrasonic transmission can be used for communication trough hulls and bulkheads of naval vessels, chemical storage tanks, aircraft and spacecraft fuselages, hydraulic accumulators, or hermetically sealed pressure chambers [19]-[23]. However, ultrasonic communication will be limited for applications where foam isolation is required, such as reefer containers. Therefore, this issue will require further research in the future.

In order to generate the ultrasonic signal, piezoelectric technology has been selected over laser generation and electromagnetic acoustic transducers (EMAT) due its mayor maturity. Besides, it allows smaller sizes, power efficiency and cost reduction [24]. However, the main challenge associated with the acoustic techniques is the induced multipath effects, which can lead to Inters-Symbol Interference (ISI). This drawback will be minimized for this application by using a low resonance frequency.

The selected piezoelectric transducer is Prowave 400EP250, with a resonance frequency at 40 KHz. A so low carrier frequency has been used in order to minimize the attenuation and multipath effects, and because a high data rate is not required.

The modulation scheme chosen to transmit the ultrasonic wave was DBPSK, which is typically used for low data bandwidth applications, because it allows a very simple non-coherent demodulator implemented by software.

The basic scheme is illustrated in Figure 2, where the transmitter is inside the container (top of the figure) and the receiver outside (bottom).

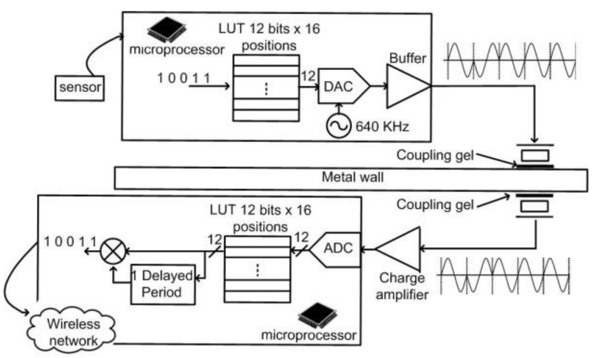


Figure 2. Scheme of the Ultrasonic Communication

In the transmitter side, Fig. 2 shows how data from the different sensors are collected by the microprocessor. A *Look-up-table* (LUT) with a depth of 16 values and width of 12-bit stores the samples of a 40 KHz-sine wave. These samples are picked by the embedded 12-bit DAC at 640 KHz according to the sensors data to generate a DBPSK modulated signal.

Bit time has been adjusted to 16 cycles of the carrier frequency ($f_c = 40\ kHz$) in order to maximize the robustness in the reception. Therefore, the bit rate $F_b = 1/T_b$ is equal to 2.5 Kbps and the bit time $T_b = 16/f_c = 400\mu s$. Experimentally, the measured 3-dB bandwidth of the transducer is around 10 KHz, higher than the 5 KHz required for this data rate.

The analog DBPSK signal generated is buffered and used as the input of the transducer. The transducer, placed on the metallic wall, is installed by using an acoustic coupling gel, whose function is to adapt acoustic impedance, maximizing the transmission of energy from one medium to another.

The received acoustic signal, outside the container (bottom of Fig. 2), is translated to an electrical signal by a faced transducer. Then, it is buffered and amplified by a high gain charge amplifier in order to obtain a full-scale signal at the Analog-to-Digital Converter (ADC).

The scheme of the charge amplifier is shown in Figure 3a. It is based on an operational amplifier with a negative feedback loop made of a capacitor ($C_f$) and a resistor ($R_f$). These elements implement a high pass filter with its cutoff frequency at $1/2\pi C_f R_f$, as illustrated in Figure 3b [25], where $S_{VQ}$ is the sensitivity of this stage (inversely proportional to $C_f$). A value of 10 pF for $C_f$ and a $R_f$ higher than 400 KΩ have been selected in order to maximize the sensitivity and to place the signal band in the pass-band of the filter.

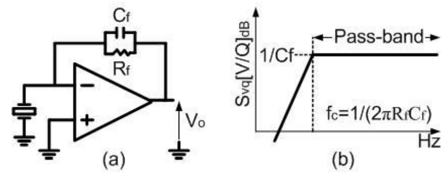


Figure 3. Charge Amplifier Circuit (a) and Frequency Response (b)

This ultrasonic front-end is installed as part of the transponder controller (described in Section IV.C), which will send the demodulated data to the wireless network.

### *C. Transponder Controller*

The transponder controller, located outside the container, demodulates the ultrasonic signal, and sends the information to the hub or gateway of the wireless network. This board is controlled by another STM32F103RD microcontroller, which uses a 1Mb EEPROM Memory (24LC1025) to store temporary data. Each measurement has associated its data time stamp obtained by a real time clock (RTC).

### *D. Wireless network*

IEEE802.15.4 standard was selected to implement the wireless network, because it allows a low data rate communication with very low power consumption, extending the battery life. Other features of this standard are listed in Table III.

TABLE III
IEEE 802.15.4. 868/915MHZ FEATURES

| | |
|---|---|
| Range | 10-1000m |
| Latency | <15ms |
| Data rate | Up to 20/40 Kbps (802.15.4-2003)<br>Up to 250 Kbps (802.15.4-2006) |
| Channels | 11 |
| Addressing modes | 64bit (up to $2^{64}$ devices) |

There are two physic layers available in ISM (Industrial, Scientific and Medical) band: 868/915 MHz and 2.4 GHz. The area covered by the wireless network grows when frequency decreases, mainly in hostile environment such as containers yard or ports. Therefore, the selected physic layer is 868/915 MHz band. As needed data rate is lower than 20 Kbps, the BPSK modulation scheme with 20 Kbps has been selected, compliant to IEEE 802.15.4-2003/2006.

The network is implemented by using the One-Go End Devices from the company Adevice Solutions. These end-devices communicate with the hub device in a tree topology wireless network. Hub device is the upper element of the wireless network, working as the gateway between the IEEE 802.15.4 network and the management platform, which receives the data by an internet connection. This internet connection can be Ethernet for fixed locations (ports, depots,…), mobile (GPRS/3G/4G) for land areas and Satellite for maritime spaces. Finally, the hub device, instead of each end-device, also provides the GPS position. Thus, although the location accuracy is slightly decreased, the total power consumption is enormously reduced.

### *E. SOS Server and data browser*

This element stores received data and provides the management functionalities and the monitoring and tracking information to the end user. It is composed by two sub-systems: the SOS (Sensor Observation Service) Server and the Viewer.

The SOS Server is based on 52º North Geospatial Open Source Software and offers a standard user interface to work with the received measurements, including the SensorML standard in order to model the sensors data by using a XML format. The Viewer incorporates a SOS client in order to present the information stored in SOS Server (GPS Position, temperature, humidity…) and display it by using a web viewer (Fig. 4). This browser is composed by different layers, which can be activated or deactivated by the end user.

Figure 4. Viewer Interface

## V. Implementation Aspects

Enclosures of acquisition board and transponder controller must fulfill two main requirements: ruggedization and miniaturization. A package (model B 140804 ABS 7035) was selected, with IP 66/IP 67 classification and dimensions of 150x80x40mm$^3$. This size was chosen with the objective of fitting these devices in the corrugated surface of the containers, providing them an additional protection in a real implementation. Moreover, both packages have to be faced in order to implement the ultrasonic communication. Finally, a third ruggedized package (T 205 model, with dimensions of 52x50x35mm$^3$) is used to allocate the temperature, humidity, motion and magnetic sensors. These three packages installed in the container are illustrated in Figure 5.

Another implementation aspect is a secure fixing of these enclosures over the metallic surface. With this objective, four BMN4-16 Neodymium magnets were selected, capable of supporting 9.5 Kg each one.

Finally, about the cost factor, the full-system has a scalable price, being 200-300€ per container. Thus, it is worth the investment, taking into account that the value of the load is typically between 10.000 and 40.000 Euros for fruits, and up to several million Euros for pharmaceutical products [4].


Figure 5. Transponder controller outside the container (left) and acquisition board inside the container (right)

## VI. Experimental Results

### *A. Ultrasonic System*

Before the integration with the whole system, the metallic channel based on ultrasonic communication was separately tested by using the schemes of Figure 2 and 3a. The container wall was firstly emulated using a metallic barrier of 1x1x0.01 m$^3$, thicker than necessary (container walls thickness are around 5-7 mm). The charge amplifier has been implemented based on the operational amplifier OPA350 of Texas Instruments. Experimental results shows 12 $mV_{pp}$ amplitude signal at the output of the transducer outside the container when a 3.3 $V_{pp}$ (36.3 mW) is applied at the input of the inner transducer. The 3-dB bandwidth is 10 KHz, enough to meet the 2.5 Kbps data rate requirement detailed in Section IV.B.

With the objective to place the presented system into the state of the art, a comparative study of ultrasonic metallic transmission systems is drawn in Table IV, where only [21] uses EMAT instead piezoelectric technologies. It is possible to observe how a higher data rate requirement means a more complex modulation process, such as OFDM [22]-[23], when frequency-selective fading and multi-path propagation effects are introduced in the communication channel. Additionally, the high attenuation through the metallic channel for high frequencies results in relatively high power consumption, leading to very high input signal levels. Only [20] is a low power implementation, with a lower data rate for a thinner bulkhead than the proposed system.

Finally, in the final implementation of the proposed system, this power is only consumed during the transmission time, which is 108.8 ms (being periodically sent each 1 hour), due to the information frame has 34 bytes.

TABLE IV
Comparison Between Different Related Works Based on Ultrasonic transmission

| Publication | Data rate (Kbps) | Modulation | Voltage / Power Input | Bulkhead Thickness (cm) |
|---|---|---|---|---|
| [19] | 0.435 | AM | 10 V | 15.24 |
| [20] | 1 | AM | 30 mW | 0.7 |
| [21] | 1000 | QPSK | 1230 mW | 2.54 |
| [22] | 15000 | OFDM | - | 6.35 |
| [23] | 17370 | OFDM | 31 V | 6.35 |
| This work | 5 | DBPSK | 3.3V/36.3 mW | 1 |

### *B. Experimental Results*

As a previous step, sensors inside the container were satisfactorily tested. Temperature, brightness and humidity sensors were tested taking measures periodically each 1 hour during 4 days. Accelerometer, motion and magnetic sensors were validated being excited each 30 minutes approximately during 15 hours. The time-stamp of each measurement was validated as well.

The next step was to verify the correct performance of the transponder controller, checking the data received from the ultrasonic front-end, the communication with the wireless transceiver and the stored temporary data.

About the wireless network, the correct communication between the hub and the end devices, and the GPS position values, were validated. Additionally, the end device reconnections were successfully implemented, obtaining a cover area of around 500 m, higher than the requirement (around 150 m) initially estimated.

Table V illustrates the reliability of the system, showing the final results obtained for three different test benches with three cargo containers monitored simultaneously.

TABLE V
MEASUREMENT RESULTS

| Test bench | Periodic Meas. | Correct Periodic Meas. | Meas. of events | Correct Meas. of events | Total Meas. | Correct Meas. |
|---|---|---|---|---|---|---|
| 1 | 62 | 98.38% | 20 | 100% | 82 | 98.78% |
| 2 | 67 | 98.51% | 81 | 97.53% | 148 | 97.97% |
| 3 | 300 | 98% | 973 | 97.12% | 1273 | 97.33% |

Finally, in order to validate the *SOS Server and data browser* some tests were implemented with the objective to check the correct detection of the containers and their location in the map. A view of these functionalities was previously illustrated in Figure 4.

## VII. CONCLUSIONS

In this paper, a feasible system for intermodal freight transport with electronic management and tracking of goods applications has been presented, describing each of its parts: an internal intelligent configurable sensor network, a non-invasive and low power through metal ultrasonic data communication, a long range and low power scalable wireless network IEEE 802.15.4 at 868/915 MHz for harsh environment applications, and a management subsystem for tracking, monitoring and alarm reporting purposes. The integrated system has been experimentally tested and means a competitive contribution to the intermodal freight transport regarding costs, worldwide compatibility and sealing preservation of the monitored cargo containers.

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