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# ZigBee-based wireless transmissions interface incorporated to an FPGA embedded system

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**Abstract:** An application that uses ZigBee modules to transmit signals of ECG (Electrocardiogram), Intraventricular Pressure (IVP) and Intraventricular Volume (IVV) from a Conductance Catheter System (CCS) is presented. Wireless interface is developed using ZigBee modules. One of these modules (‘COORDINATOR’) is connected to a PC and receives signals from the remote module. The last, configured as an ‘END DEVICE’, collects signals from the digital CCS. Data including biomedical signals are previously processed using a Field Programmable Gate Array (FPGA) device. ZigBee technology ensures robust communication with very low power consumption, a feature that makes it suitable for implantable biomedical devices.

**Keywords:** CCS; conductance catheter system; wireless transmission; ZigBee; FPGA.

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## 1 Introduction

In a broad sense, Telemedicine or Telehealth generally refer to the use of communications and information technologies for the delivery of clinical care. Telehealth adds a new paradigm in healthcare where the patient is monitored between physician office visits or continuously at home.

Through wireless technology, patient's vital signs are monitored embedding sensors into wireless biometric devices at home (Jung and Lee, 2008; Junnila et al., 2008; Kim et al., 2007; Dagtas et al., 2007) or even into clothes (Kuryloski et al., 2009; Seppä et al., 2008; Lahtinen et al., 2008; Vuorela et al., 2008; Seppä, 2007). Then, the collected information is transmitted through a communication network to a remote station for medical analysis.

Step further, implantable wireless medical devices have made possible the management of patients with health chronic disorders. In this context, Congestive Heart Failure (CHF) – a disorder that affects the ability of the heart to efficiently pump the blood – is the disease that produces the greatest number of hospitalisations in the USA and Europe (San Román Terán et al., 2008; Fang et al., 2008) and also results in pathological conditions that require monitoring and medical management.

Data from clinical trials have shown that a large number of patients hospitalisation for CHF occurs as a result of venous congestion and volume overload (Fonarow et al., 2007, 2008; Allen et al., 2008). It has been suggested that remote monitoring of ambulatory CHF patients could improve the long-term management of them (Hunt et al., 2001).

A recently evaluated implantable device makes it possible to monitor fluid accumulation in chest (congestion) using impedance intrathoracic measurements (OptiVol, Medtronic Inc) (Yu et al., 2005).

Other developments are able to transmit vital signs such as blood flow, pressure, ECG and temperature (Axelsson et al., 2007).

To assess the haemodynamic state in CHF patient, pressure in the right heart side is recorded and transmitted using transvenous leads, but dissociation between changes in this parameter with progression of CHF was reported (Shaha et al., 2002).

Another technique used to assess CHF progression is the CCS. By means of left heart catheterisation, CCS records left IVP and IVV. This invasive technique can only be implemented during surgery or in haemodynamic rooms. In this way, our research group is developing an implantable fully digital CCS (Gómez et al., 2010), which transmits IVP, IVV and ECG signals wirelessly to a remote station.

This paper presents the design and evaluation of a wireless transmission system for cardiac signals (IVP, VIV and ECG) and the necessary amendments implemented in the digital CCS previously developed on FPGA-based conductance catheter design (Gómez López, 2008).

## 2 Design

The telehealth devices incorporate short-range and low-power consumption wireless transmission protocols, being Bluetooth and ZigBee the most commonly used.

Even though only the ZigBee protocol – based on the IEEE 802.15.4 standard – contains specifications for medical applications, there are a large number of approved medical devices that use both protocols.

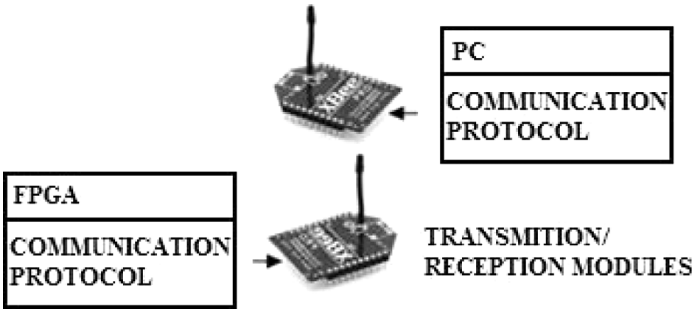
In our case, ZigBee protocol has been chosen because it optimises power consumption, and thus, maximises battery life.

Figure 1 presents a complete system scheme including:

- The FPGA-based CCS, which incorporates the logic functions required for data transmission and a ZigBee transmitter module.
- The ZigBee receiver module connected to a PC, which displays signals.

A ZigBee evaluation kit (XBee PRO ZB, Cika Digi) is used. It includes two wireless communication modules and two USB2UART boards used to create a serial port from a USB port. Each module is a configurable modem that implements the ZigBee communication standard protocol.

**Figure 1** Scheme of the whole system



The ZigBee receiver module is configured as ‘COORDINATOR’ while the module connected to the CCS – transmitter module – is configured as an ‘END DEVICE’ because it can operate in low-power consumption mode.

Both modules are operated in Application Programming Interface (API) mode, which allows better management of network properties.

Data conditioning is implemented in a reconfigurable FPGA device (FLEX10k70RC240, Altera). Logic equations are configured in the FPGA using MAX+PLUS II development system. Digital design is performed using graphical editor and hardware description language (AHDL).

A graphical interface, implemented in LabView, allows reading and saving – in text file – the data from the emulated serial port. Then, biological signals (IVV, IVP and ECG) are plotted in the personal computer screen.

## 3 System description

Digital data (eight binary digits per each value) are recorded in a ROM memory. This memory provides data to another RAM read/write memory, which is used to generate the message to be transmitted using ZigBee protocol. Both memories are included in the FPGA device.

When the transmission is requested, each byte of the message, one by one, is extracted from RAM and it is converted to serial protocol (RS232). Then, it is inserted into pin 3 ('DIN') of the transmitter module (END-DEVICE) (Figure 2). The END-DEVICE stores data in a buffer until wireless transmission to the destination address specified in the message is performed. The enable input (START) – which starts the message transmission – is connected to the END-DEVICE output 'DIO2'. Pin 'DIO2' state is changed to low wirelessly when transmission is desired. While the 'DIO2' output is low, the end-device keeps awake and the FPGA message generation is activated.

To generate a message, 56 RAM addresses are used (Figure 3). At the first 17 RAM addresses, a 17-byte fixed header is recorded. Within each message, there are 34 bytes of IVV, IVP or ECG signals. In the following 34 addresses, 34 bytes of data (provided by ROM) are written in the RAM. Finally, a check byte is written in the last RAM address.

A guard time of 24 bits (3.5 ms) is generated between messages.

**Figure 2** Block diagram to carry out biological signal transmission

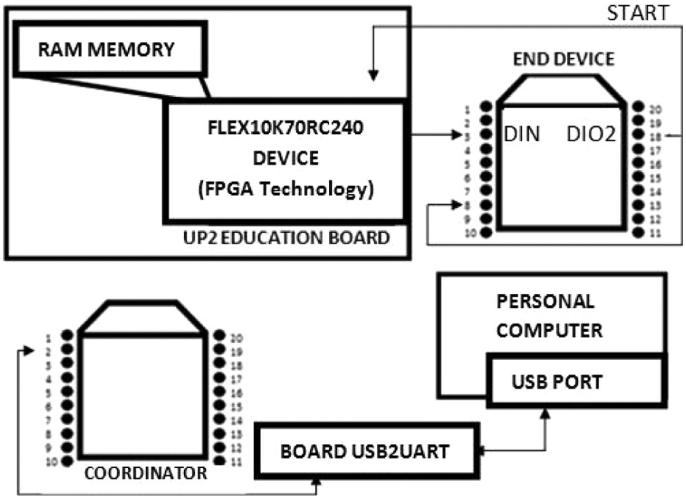
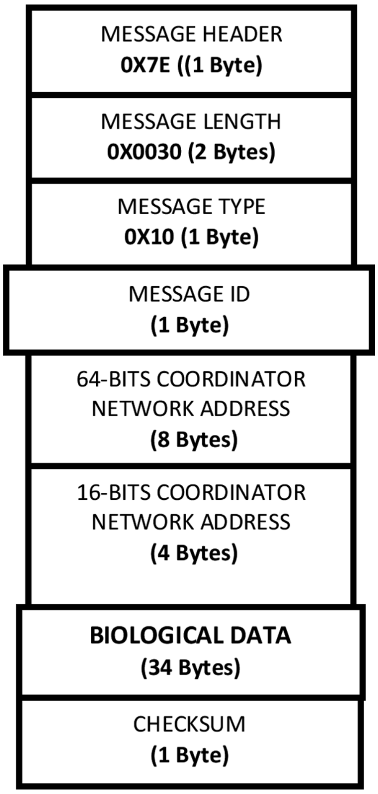


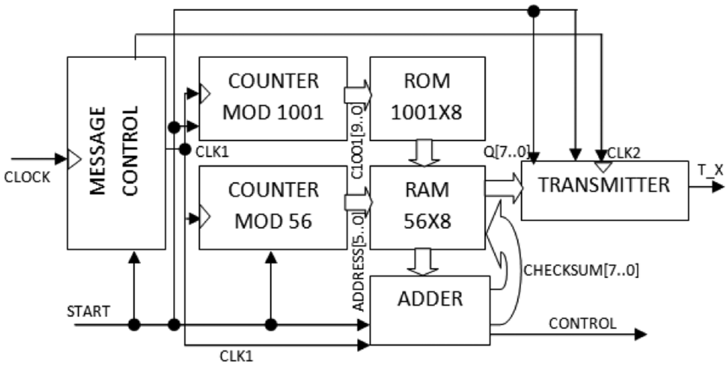
**Figure 3** FPGA generated messages description (see details in text)



## 4 FPGA-based logic design

Figure 4 shows a block diagram of the FPGA-based logic design implemented in the FLEX10k70RC240 device. The system has two inputs (START and CLOCK) and one output (T_x), which is connected to pin 'DIN' of the END DEVICE (Pin 3) (Figure 2).

**Figure 4** Logic built into the FLEX10k70RC240 device using MAX + PLUSII program



When the START input changes to low state, the following actions occur:

1 MESSAGE CONTROL module is restarted. This block creates both, CLK1 and CLK2, from the FPGA main CLOCK.

  - CLK1 is implemented with a counter. The carry output of this counter is used as an 872 Hz-synchronous clock. Its frequency is 11 times slower than the RS232 serial protocol frequency (9600 bps). Note that to serialise one byte using RS232 protocol, are necessary 11 CLK2 pulses.
  - CLK2 provides a 9600 bps-output frequency. This frequency is used to serialise the data (RS232 protocol).

2 COUNTER MOD 1001 and COUNTER MOD 56 modules, which control the addressing of ROM and RAM memories, respectively, are also restarted.

3 SUMA block is restarted. It generates a byte (CHECKSUM) to detect if the message has been successfully generated. The resulting CHECKSUM byte is written in the 53rd RAM address. A guard-time, where no data are transmitted, is also generated by SUM module between two consecutive messages to prevent data loss. During guard-time, COUNTER MOD 1001 module is disabled keeping constant the ROM address.

4 TRANSMITTER module, which is implemented as a finite-state machine, is restarted. It is responsible for serialising data provided by RAM memory (D [7.0]). It also allows adding the start-bit, parity-bit and stop-bit required for serial communication.

A total of 1001 data bytes corresponding to biological signal (IVV, IVP or ECG) are loaded into a ROM memory configured in the FPGA device. The 8-bits memory output is used as an input for RAM memory. Each message is composed by the bytes at the output of this memory (D [7.0]).

During the first 17 states of COUNTER MOD 56 module, the bytes at RAM output are the message header. In this period, the RAM is set in ‘read mode’. During the next 35 pulses of CLK1, the RAM is set in ‘write mode’ to receive data from ROM memory and from SUMA module. Therefore, the data are placed in the memory output during the first 52 states of the COUNTER MOD 56 module to be later admitted by the TRANSMITTER module, where the data are serialised and sent to the END DEVICE. During the following four states of COUNTER MOD 56 module, the TRANSMITTER output is in HIGH state (‘idle’ state in RS232 protocol) generating a guard time in which the END DEVICE does not detect the presence of any bit. Then, the COUNTER MOD 56 is restarted. Finally, the END DEVICE packs and sends, during the guard time, the 52 bytes previously received.

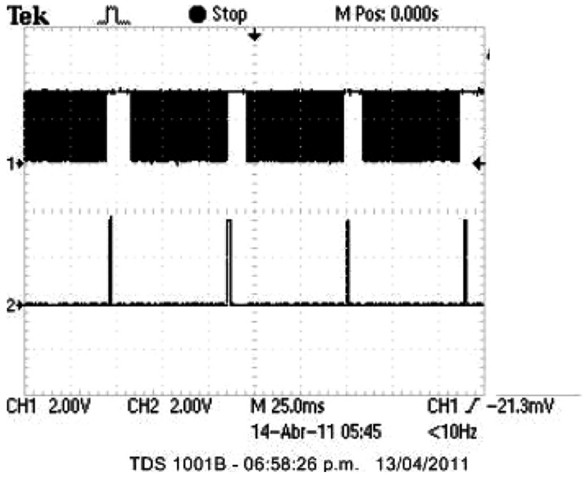
The described logic design was developed, compiled and incorporated into the EPF10k70RC240 device using the MAX + PLUSII program and the UP2 educational board.

## 5 Results

### *5.1 Transmitted message flow*

Figure 5 shows the message flow – from the Coordinator to the computer – on the oscilloscope screen (TDS 1001B, Tektronik) as a function of time. Channel 2 signal is generated by the FPGA when COUNTER MOD 56 module is restarted. For each positive pulse of this signal a message is received by COORDINATOR module connected to PC (Channel 1).

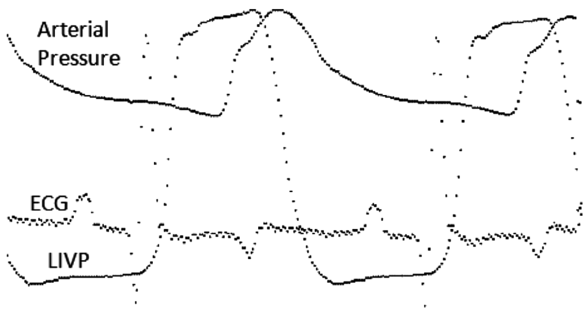
**Figure 5** Flow message. Top: Data packets as function of time. Dark area corresponds to the transmitted data. It can be seen the guard time between packets. Bottom: the sync pulse that triggers the transmission of each packet



### *5.2 LabView-based display*

Received data visualisation is performed using LabView-based graphical user interface (Figure 6), where data packets – corresponding to biological signal – are extracted from each message. Biological data are stored from 15th to 49th byte in each received packet.

**Figure 6** Computer screen where the biological transmitted signals are presented as a function of time (superimposed) using a graphical user interface LabView-based. ECG, arterial pressure and intra-ventricular pressure are sequentially presented from top to bottom



### *5.3 Transmission rate*

To avoid data loss, a transmission period higher than 50 ms (20 Hz rate) is suggested (ZigBee standard). In this context, it has been proven that no data loss occurs if packets with a maximum load of 84 bytes are transmitted using a transmission period less than 50 ms (Pinedo and García, 2008).

In this paper, a 52 bytes message is generated by FPGA. For message transmission, a 64 ms transmission period is used, which is equivalent to a 15.6 Hz transmission rate. Therefore, the bit transmission rate is 6500 bps, and the effective transmission rate, considering that only 34 data bytes of IVV, IVP or ECG signals are transmitted within each message, is 4250 bps.

### *5.4 Transmitted data error*

A check-byte at the end of each message is included according to ZigBee protocol (CHECKSUM in Figure 3). Receiver module verifies this byte on received messages to detect if the data has been transmitted successfully (check data integrity). If no match is found between generated and received check-byte, a failure message is send to transmitter. This module resends the message up three times, if the error persists the message is discarded.

Note that using ZigBee wireless standard protocol, which includes a check-byte in each message or a similar integrity control system, the message received matches perfectly with the original one.

## 6 Discussions

The emphasis has been on developing a wireless transmission system for biological signals based on the ZigBee protocol. A few considerations regarding the design described previously deserve to be discussed.

As mentioned, the wireless transmission is performed by data packets. Every packet must be stored in a buffer in the END DEVICE. In turn, the END DEVICE packs and sends the data if during the time equivalent to 12 bits serialisation no data is received at pin 3 (DIN). The latter is set by default but is likely to change.

This memory-buffer can become saturated, in which case, the whole packet – in the END DEVICE's buffer – is discarded.

To avoid losing information by buffer overflow, a flow control signal called CTS (Clear To Send), normally active LOW state, is used. In our design, 17 bytes before the buffer fills up, CTS switches to HIGH state indicating to the FPGA device to stop sending information to the wireless module.

Another approach for avoiding buffer saturation and packets loss is properly set times so that the buffer never reaches saturation; this is achieved by in compliance with the guard time between messages.

ZigBee protocol specifies a maximum load of 84 bytes per message; this can contain up to 66 bytes of information. To no loss messages, the higher transmission rate must be 20 Hz (which means a 50 ms transmission period). So, the maximum bit transmission rate is 13.440 bps, and the maximum effective bit transmission rate is 10.560 bps.

The real-time transmission of a biological signal sampled at 200 Hz requires a 1600 bps transmission rate, hence to transmit three of these signals a 4800 bps transmission rate would be necessary. Therefore, the ZigBee protocol allows us to transmit online the signals selected.

In our application, 'real time' is defined as the ability to display data on a PC with a maximum delay time that coincides with the time required for the generation and transmission of 'one' packet information; this is 64 ms.

## 7 Conclusions

The ZigBee-based wireless interface has been developed and successfully probed using the previously designed FPGA-embedded CCS. Besides the XBee modules, no digital or electronic component has been added to CCS.

Because of ZigBee protocol, END DEVICE can be wirelessly configured reducing the power consumption.

It also allows implementing security mechanisms to increase system reliability; because of the 'ckeck-byte' included at the end of each packet, the reception and visualisation of erroneous messages is no possible.

The major conclusion is that the ZigBee protocol easily and accurately implements wireless transmission of biological signals. Also, the possibility of configure security systems and reduce power consumption makes this protocol very suitable for implantable biomedical devices.

Furthermore, heart failure patient monitoring by wireless data transmission could be improved by the ability of the developed system to achieve data collection without patient interventions or catheterisation. Finally, this system requires an exhaustive analysis in the near future.

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