DESIGN OF A WIRELESS PULSE OXIMETER USING A MESH ZIGBEE SENSOR NETWORK

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Abstract: This work describes a prototype to convert a conventional pulse oximeter into a wireless device. Samples have been taken from a commercial Nellcor DS-100A probe using an FPGA. This programmable device is integrated with an XBee wireless modem; using ZigBee protocol, data is sent through the wireless network to a central server. The system generates alarms to the medical staff when vital signals are critical. Data can be saved in a database allowing the review of monitored data furthermore, with these data, future research on medicine can be started.

1 INTRODUCTION

In hospital, life constants of patients are monitored by several systems, most of them use wires to connect sensors to the monitoring device. These systems are not comfortable and their mobility is reduced, the hindering the medical work. Most of these devices do not record the history of the monitored constants.

This work presents the adaptation of a conventional pulse oximeter (Tremper et al., 1989) (Kamat, 2002) (Baran, 2006) to suppress its wire, sending data in real time through a wireless sensor network. Data can be stored in a PC, allowing the review of monitored data; furthermore, with these data future medical research can be started.

Pulse oximeter was the first device adapted, future works will comprise other devices as non-invasive blood pressure, temperature, fetal heart rate, uterine contractions on labor, and, WHO partogram.

Telemetry wireless (Jovanov et al., 2000) (Hameed, 2003) monitoring will allow the patient mobility. By using wireless monitoring, both patient satisfaction and working conditions for the staff is expected to improve.

There are Bluetooth wireless pulse oximeters in the market (Morón et al., 2005) (Nonin Inc., 2010). In this work, ZigBee is the selected communication protocol used in the wireless sensor network. Bluetooth requires higher power consumption than ZigBee. Another difference is that Bluetooth devices use a point to point directive whereas ZigBee devices constitute a mesh network enabling flexible connection of new sensors.

2 ROUTING IN ZIGBEE MESH NETWORKS

Pulse oximeter is a critical device and, therefore, it needs real time communication, low latency, and the possibility of alternative routes in case of connection problems in remote monitoring. These requirements make the mesh topology as the most appropriate.

The end-devices are Reduced Function Devices (RFD) that can be in sleep mode periodically. They cannot route and always send their data to their parent node (a router or a coordinator). In the association stage, the end-device selects its parent and receives a notification with a short 16bit address. If the end-device is restarted, it is declared as an orphan and immediately, its router resends its short 16bit address in order to enter into the network again. If this process fails, the end-device will make the association process again, until it can be associated to another parent.

The main mission of a router consists in forwarding data through the network and managing the information of its end-devices as a buffer until they wake up. The end-devices sleep periodically and send a "Data Request" frame when they wake up. The parent can send data stored in its buffer
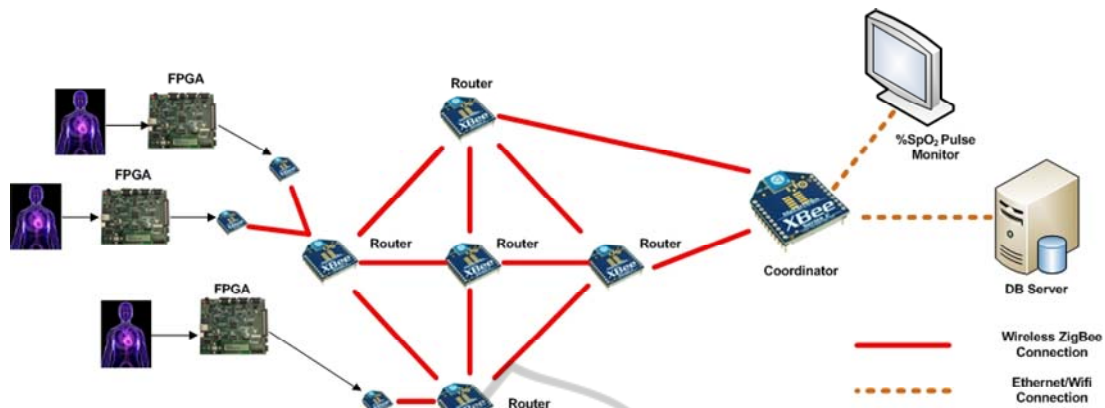
Figure 1: Global system and network architecture.

to the end-devices.

In mesh networks, routers and coordinators discover the route to the destination point using messages at network level as "Route Request" and "Route Reply". If there is no direct communication, messages will pass through the routers until they reach their destination. It is possible to detect if the route fails, thanks to the acknowledgment (ACK) procedure held by 802.15.4. The router will search for a new route in order to be able to send data to the destination. In a full mesh network with n nodes, each node has a link with the others n-1 nodes, with a total of n(n-1) links. These topologies (partial-mesh and full-mesh) can be set up by adding new router nodes, with the subsequent increase of energy consumption.

3 SYSTEM DESIGN

This work attempts to implement a wireless pulse oximeter using ZigBee mesh network. Figure 1 shows the architecture of the network.

To design a Wireless Pulse Oximeter, the following components have been used: Rabbit RCM4510W, XBee USB, FPGA Spartan, Pulse Oximeter Nellcor, and PC Windows XP.

3.1 Pulse Oximeter

Nellcor DS-100A is a popular pulse oximeter used in hospital, and therefore it has been selected to use in this work.

In order to couple the Pulse Oximeter with the FPGA is necessary to know the timing diagram of Nellcor (Webster, 1997), shown in Figure 2. The Nellcor pulse oximeter system uses a four state
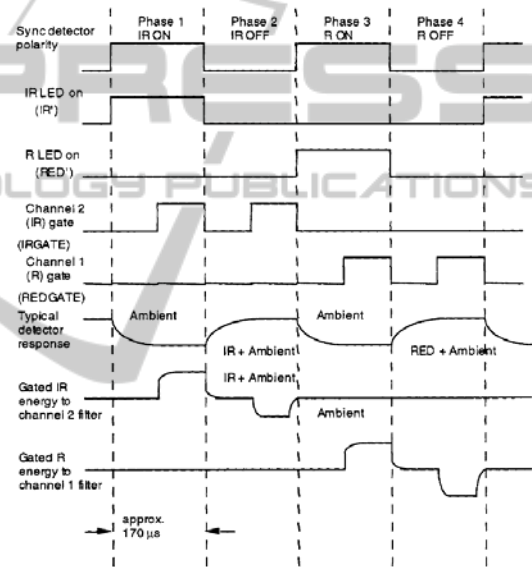

Figure 2: Timing Nellcor Diagram.

clock, or has a duty-cycle of 1/4, as compared to the Ohmeda (Webster, 1997) system, where the duty cycle is 1/3.

In the first quarter, the IR LED is on, whilst the R LED is on in the third quarter. In the second and the fourth quarters, these LEDs are off. During these periods, ambient light measurements are done. The gate pulses are the sampling pulses applied to the input signal to separate out the R and the IR components from the input signal. The sample pulse during the OFF period of the respective LED is used to sample the ambient. The gradual rise or fall of the pulses is due to the transients, which are smoothed out using low-pass filters. The ambient light component is larger in the four quarter, compared to the value in second. Using suitable values for the gain in the programmable DC offset amplifiers, this

ambient light component can be eliminated. The AC plus the DC components of the R and IR signals are digitized in the FPGA in order to send this data to the Rabbit RCM4510W.

3.2 FPGA

The FPGA used in this work is a Spartan 3E equipped a XC3S500E chip. In this FPGA, a MicroBlaze processor has been designed, with a Delta Sigma AD converter IP Core included.

Xilinx Platform Studio (XPS) software was used in this work. This software has been developed to manage the probe and to obtain the received information in the photodiode. These data are processed in order to obtain the values of pulse and SpO_2. These values are sent to the parallel port of the RCM4510W.

The information is processed in the FPGA and it is sent to the Rabbit via parallel port. Rabbit decrypts this information and prepares the packet in order to send it to its destination. Both, pulse and oxygen values are sent on real time to the Database Server (DBS).

3.3 Rabbit RCM4510W

RCM4510W RabbitCore is the ZigBee hardware used to transmit the pulse oximeter data to the coordinator. It is equipped with an on-board ZigBee/802.15.4 modem for wireless connectivity. Features also include 512K flash memory and SRAM, 40 general-purpose I/O, and up to 9 general-purpose I/O, 4 of which can be set up as analog inputs via the ZigBee module.

The RCM4510W has a Rabbit 4000 processor at 29.49MHz. Other features include hardware DMA, auxiliary I/O, quadrature decoder, input capture, GPIO lines shared with up to five serial ports, and four levels of alternate pin functions that include variable phase PWM.

3.4 Xbee USB Coordinator

The coordinator is the most important element of the network and therefore there should be one in a network. The main function is to monitor the state of the network and establish the routes that devices have to use in order to send the information.

Java library Xbee-api.lib has been used to extract the information from the coordinator. XBee class is the main communication interface between a module XBee and gateway to the wireless network. This class coordinates the sent and received data by packages. After the instantiation of the Xbee class,

the system will start to manage the information of the network. The coordinator XBee USB is connected to the COM3 port at 9600 data rate.

The software for managing the network has been successfully developed to receive data from the probe, and, to send it to the DBS.

3.5 Database Server

The DBS is implemented using MySQL Server over a Linux Machine. This database stores the following information about patients:
- Patient name
- Sex
- Age
- Historical Pulse
- Historical % SpO_2
- Drug treatment

Future researches will allow further processing of the information about patients. Thus, the system is able to determine real time if any patient suffers from a cardiac or respiratory problem. In this case, an alarm will be generated to inform to the staff. Other possibilities are to compare multiple histories to study population responses; responses after different drug treatment, etc.

4 RESULTS

The reliability of the network and the developed pulse oximeter was tested with these experiments:

4.1 Packet Tests

To check the reliability in the communications, it was developed a program to count the number of packets received in the coordinator. The test was carried out using 5 Routers, and 3 End devices. Electromagnetic contamination with Bluetooth and Wifi signals was introduced.

The first test starts with the previously presented configuration and the number of transmitted packets reached 100%.

The second test tries to eliminate the connection between the End device associated to the pulse oximeter and its parent node. When the route crashes, the End device has to re-associate to another router. This operation delays for approximately 2 seconds (Casilari, 2010). In this time, the node cannot transmit to the coordinator, however it stores data in a buffer to avoid the loss of data. When the node re-associates to another parent, it sends the
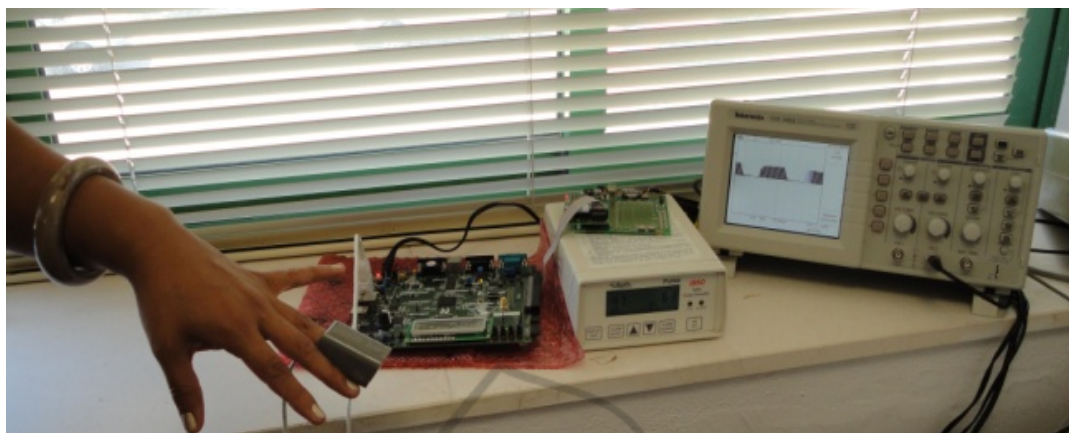
Figure 3: FPGA, RCM4510W and Nellcor Probe.

stored data in the buffer and continues normally. During these 2 seconds, the display at the coordinator shows the last received pulse and SpO_2 values. When the end device sends the new data, it is processed and printed on the coordinator display and stored in DBS.

If all routers crash, the End device tries to detect if a direct connection to the coordinator is available. As the network is redundant, when the End device looses the connection to its parent, it reconnects directly to another router transparently to the user.

4.2 Measurement Tests

In order to test the correctness of the data obtained with the pulse oximeter integrated with the FPGA, a comparison between these data, and those acquired by a professional ISSO certified pulse oximeter used in Hospitals, was studied.

The experiment used two probes, one of them connected to the ISSO certified pulse oximeter and the other one, connected to the FPGA pulse oximeter. The values of pulse and $\%SpO_2$ were identical in both systems.

5 CONCLUSIONS

A prototype to adapt a standard pulse oximeter into a wireless device has been proposed. Samples have been taken from a commercial probe using an FPGA. This programmable device packs the information and, as it has been integrated with an XBee wireless modem, it sends data through the wireless network to the central server. In future, FPGA and XBee will be integrated in a small wireless device supplied with batteries.

Results in terms of the reliability and technological viability have been proved to be successful. Several tests were applied to check the robustness of the system.

ZigBee provides a flexible network, which is ideal for environments were multiple sensors can be added or suppressed on-the-fly in any moment. Zigbee networks are able to operate in densely Wifi and Bluetooth populated environments. In front of Bluetooth or Wifi, ZigBee consumption is notably lower and XBee modems are cheaper. Besides, the configuration of ZigBee devices is simpler since Bluetooth has a more complex protocol.

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