ZigBee-Based Wireless ECG Monitor

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Abstract

In this paper a portable, wireless ZigBee based ECG monitoring device prototype is presented. The device is able to acquire, sample and transmit over the air a single lead ECG signal to a remote Base Station (e.g. PC, laptop), in real time. ZigBee offers an efficient relay protocol, good transmission range, flexible network structure with emphasis on power consumption efficiency. Considerations are made upon ZigBee usefulness in the field of Telemedicine and Biomedical Engineering, focusing on the trade-off between the amount of data transmitted and preservation of battery life.

1. Introduction

Wireless connectivity has been one of the prominent technological innovations of recent years, allowing freedom and ease of access to information. In particular in Telemedicine, which puts emphasis on the absence of direct contact between the patient and the physician, wireless devices are the basis for the development of efficient remote monitoring systems, able to provide continuous, real-time, and accurate information on the health condition of the patient. Due to actual size of electronic components, it is possible to integrate in a single board a device for signal acquisition, processing and wireless transmission (“motes”).

This can lead to “Body Area Networks”, where a certain number of motes can acquire a full range of bio-signals (including ECG, blood pressure, body temperature) and complementary ones (e.g. position, activity), and transmit them to a remote Base Station for processing. However, using wireless connection as a medium, a number of issues must be considered: ease of network creation, network robustness, data throughput, data loss, and in particular power consumption.

In fact, radio transmission puts a heavy load on batteries in terms of absorbed current and, in case of long term monitoring, battery life is of prime importance. In order to confront this issue, new wireless protocols have been implemented, focusing on reducing power consumption as much as possible, achieving good compromises between data throughput, covering range and robustness. ZigBee is one of the most prominent wireless protocols and we believe that transmitting real-time ECG data can be a good stress test in order to evaluate its capabilities.

2. System architecture overview

In Figure 1, the architecture of the remote sensor is shown, in terms of high level blocks.

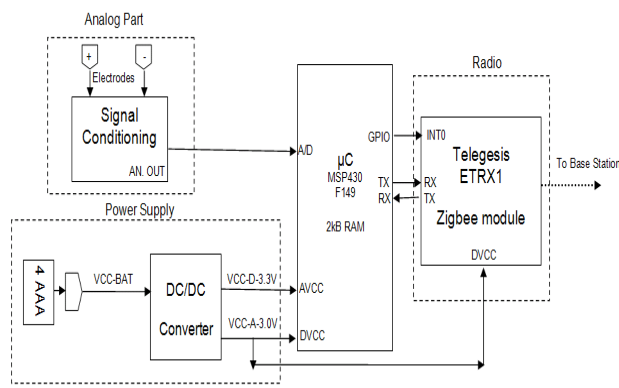

Figure 1. Architecture of the remote ECG system. The signal is acquired through a single lead, amplified, low-pass filtered and then sampled by an MSP430 Microcontroller. The sampled bytes are then sent to the transmitter Zigbee module, through UART protocol.

The ECG Monitor is the key component of the system. It consists of an analog circuit that acquires the ECG signal through a single lead (chosen among the three standard Einthoven’s leads). The signal is sampled by a low power microcontroller (Texas Instruments MSP430F149, mounted on a Multi-Sensor-Board developed by Ducati Sistemi, with an on board accelerometer, compass and GPS receiver) and transmitted over the air using a ZigBee module (Telegesis ETRX1). Currently the firmware developed supports the acquisition of either the ECG signal or the data from the sensor array.

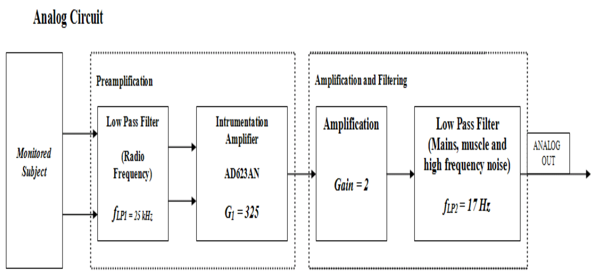

Figure 2. Analog conditioning of the signal.

When the device is powered on, the microcontroller controls the transceiver by sending AT commands (compliant with the ETRX1 firmware) through its USART module. An internal state machine is able to search for the network established by the receiver (Coordinator), joining it, and opening a transmission channel. The ZigBee protocol allows other kinds of network configurations, including mesh networks. With this topology it would be easy to extend the area covered by the sensor, using "router" nodes.

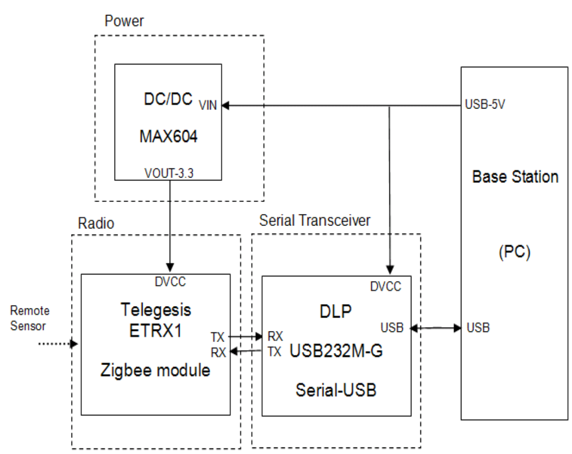

Figure 3. Receiver system and base station (PC). The data are sent to the PC through a Zigbee ETRX1 Module and a Serial/FTDI transceiver.

The Base Station (Figure 3) is composed of a Telegesis ZigBee module connected to a PC through a UART to USB transceiver form FTDI (USB232M-G). The system, in its current version, supports only a point-to-point network connection.

The end terminal can be any computer equipped with an USB port and running an operating system with an USB to UART FTDI driver. On the Base Station a Windows application reads the data stream coming from the USB port, performs filtering, and visualize the real-time ECG track on screen.

3. Data acquisition flow chain

The Data Acquisition Flow Chain can be represented as shown in Figure 4.

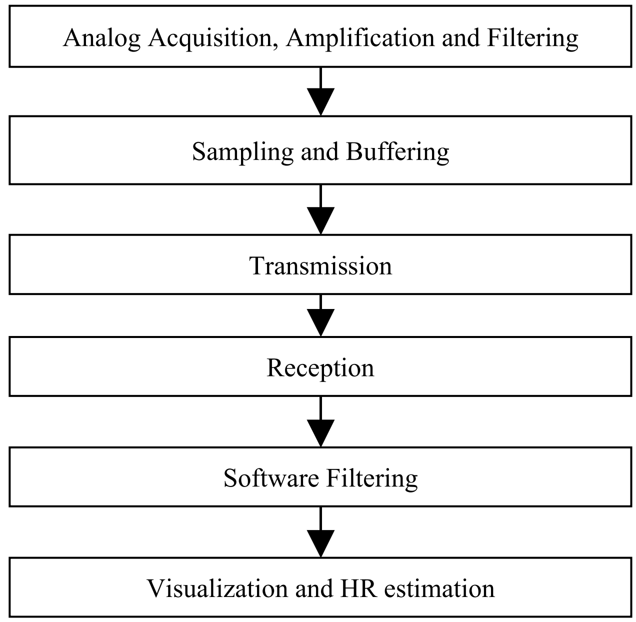

Figure 4. Data flow chain from patient ECG signal acquisition to its visualization on a remote base station.

The analog part of the circuit has been kept simple, in order to minimize board space. The raw signal is acquired through two disposable electrodes, attached to the cables through a couple of standard clips.

In the first stage the signal is preconditioned through capacitive coupling, in order to block unwanted DC components, and a high frequency low pass passive filter, in order to minimize RF interference. It is then amplified through a low power, high CMMR instrumentation amplifier (AD623). In the second stage we perform further amplification, in order to span the full range of the A/D converter, and apply a low pass filter at 17Hz, through a dual, rail to rail OPAMP. The global gain of the circuit is set at 750, allowing us to have an input range of +/- 2mV.

In a previous version of the device there was no hardware filtering, the raw signal was acquired and then processed (100 Hz Low Pass and Power line filters) on the PC. For the scope of this project a low frequency, hardware low pass-filter has been chosen since provides a very clean signal, good enough for monitoring purposes. The signal coming out from the previously described steps is sampled by the internal MSP430 A/D converter. Signal sampling frequency and resolution are respectively 500 Hz and 12 bit. Double buffering is used to prevent packet loss during transmission.

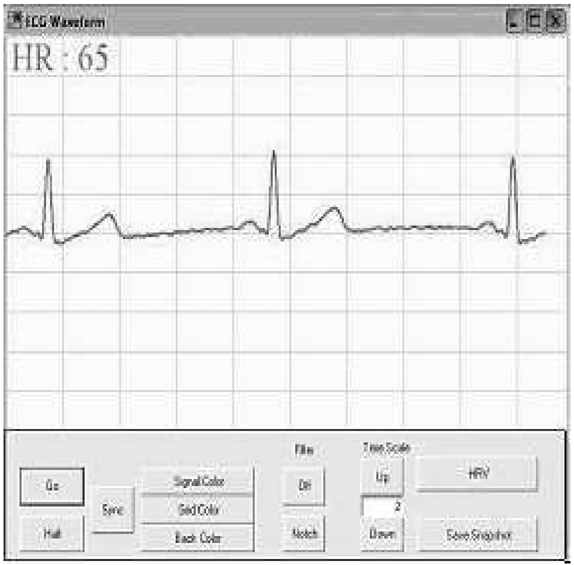

Figure 5. Signal received at the base station and visualized.

When the current buffer is full, the transmission of the bytes contained in that buffer begins and the sampling buffer is switched.

The microcontroller sends the samples, through an UART link, to the ZigBee module, that takes care of sending the received bytes over the air to the Coordinator.

The relationship between the sampling rate, buffer size and the baud rate is relevant in order to reduce power consumption as much as possible, maintaining a continuous data stream. In fact, the ZigBee module supports a deep sleep mode, in which measured power consumption is as low as 2.3 uW. Reducing the percentage of time used to transmit data can improve energy efficiency, but introduces some issues due to some hardware constraints, as discussed in the next section.

The Coordinator receives the data sent by the remote ECG Monitor via a virtual COM port created by the operating system, in order to access the FTDI module. The data is then processed by a custom developed .NET C# application, that performs real-time visualization, QRS detection and computation of some HRV parameters (SDANN and NN50)[2] .

The algorithm used for QRS detection is a variation of the well known one from Pan and Tompkins[3]. The signal is differentiated, then the absolute value is taken, and a running average is performed on the resulting signal. At this point, a dyamic treshold is computed, taking half of the difference between the maximum and minimum in a moving windows of three seconds.

The local maximum if finally identified on the original signal. Once the RR time series has been acquired is then possible to display HR and HRV information.

4. Experiments and results

A primary concern was the power consumption of the device. As seen in Figure 6, the ETRX1 accounts for the 75% of the total; there is a wide gap between the system functioning with the radio module used in transmission mode and in "deep sleep".

Analog Circuit	**31.5**	**31.5**	**31.5**
MSB (Sensors off)	**1**	**1**	**1**
ETRX1, Radio Transmission	**96.7**	**x**	**x**
ETRX1, Radio On/CPU Idle	**x**	**75.9**	**x**
ETRX1, Deep Sleep	**x**	**x**	**0.015**
Total (mW)	**129.2**	**108.4**	**32.52**

Figure 6. Power consumption of the device and radio module in different power modes

The Telegesis module can be "put to sleep" and awakened by switching the voltage level on one of its interrupt ports. We tried to come up with a storing/transmission cycle aimed at keeping the ETRX1 in sleep mode as much as possible. We would store the sampled data in the MSP430 memory and then transmitting it to the radio module in bursts. Since the official data rate of the Zigbee protocol is 250kbs (~31 KBs) and we require only 1kBs we thought we would have been able to have the ETRX1 in low power mode for several seconds.

Unfortunately one of the major limitations of the Zigbee Module is that its integrated microcontroller stores the bytes to be sent in a local buffer, of limited size. If too many bytes are sent to the ETRX1 too quickly, it won't be able to transmit them, and this will result in data loss at the receiver end, so we weren't able to set-up a store/sleep-store/send cycle as we intended to.

Another test we made was about the signal coverage of the module. The firmware provided by Telegesis provides a command that returns two indicators of the signal strength at the receiver end: LQI (Link Quality Indicator) and RSSI (Received Signal Strength Indication) [4].

Out of these two parameters, RSSI was the one that gave the most consistent results, and was chosen as the preferred indicator. In Figure 7 the results of the test are shown. As expected the RSSI is much stronger outdoor, while indoor signal quality drops quickly. Still, the coverage is good enough to cover two or three rooms, depending on the thickness of the walls and the relative positions of transmitter and receiver.

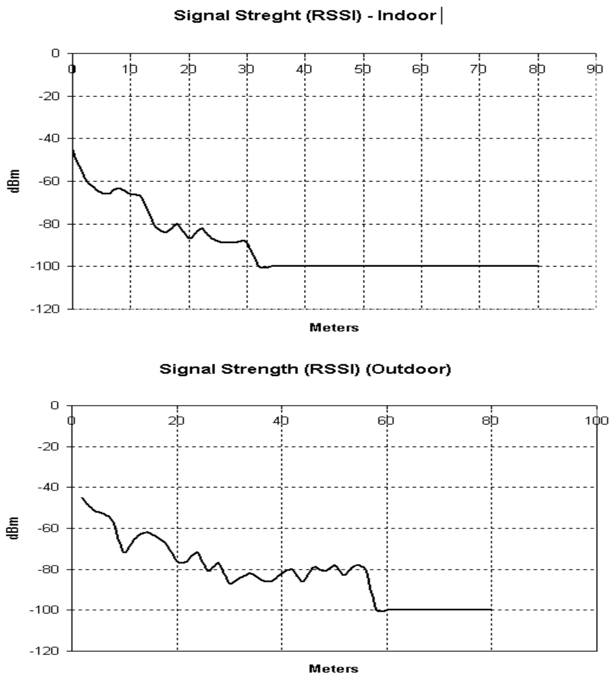

Figure 7. Signal strength (Received Signal Strength Indication, RSSI) test results, indoor and outdoor.

5. Conclusions and future work

The problems encountered during the development were mostly due to firmware constraints on the radio transceiver; in particular, the limited size of the transmission buffer didn't let us configure the radio module in sleep mode as we intended.

A possible workaround to this problem would be to reduce the amount of bytes sent over the air. This could be achieved either by using compression on the raw data, or by performing local processing on the sensor itself, in order to extract HR and HRV. The latter option is being investigated, by using XScale based Imote2 sensor [5] as a supporting platform. An additional option would be to write proprietary firmware to implement the Zigbee stack on the ETRX1 module.

Another aspect that needs to be investigated is the flexibility and robustness of the network protocol: part of Zigbee strength lies in its ability to support a wide variety of network topologies. In the use case of constant monitoring (at home or in a hospital) the range and signal strength provided by a point-to-point connection would not be adequate to provide full coverage of the environment. A network with a "sink" (the base station), the sensor, and a number of "router" nodes would be an ideal set-up.

Finally, the integration with the various sensors already available on the Multi Sensor Board, in particular the accelerometer, will complement the ECG data, allowing us to monitor the subject's activity.

Zigbee is proving to be an interesting platform for the development of medical devices. The low power consumption, good transmission range and signal strength make it a viable solution for wireless monitoring, where low/medium data throughput is required.

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