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ZigBee-Based Telemetry System

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نظام قياس لاسلكي معتمد على تقنية الزيكبي

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الخلاصة: تشهد هذه الأيام، هنالك تطورا ملحوظ في تكنلوجيا الرعاية بالصحة. الأنظمة الآنية لمراقبة الصحة تسهل حياة المريض بالاظافة الى انها تطور جودة الخدمة المقدمة لدى المشافي و مراكز الصحة. في هذه المقالة نعرض تصميم و تصنيع لجهاز قياسات لاسلكي معتمد على تقنية الزيقبي و الذي يمكن اعتماده كنظام آني لمراقبة الشارات البيوطبية. يتم تحسس و معالجة الشارات عن طريق نظامين متفرعين: النظام الفرعي الاول يتمثل في الجهاز المتحرك المرتبط بالجسم ويقوم بتحسس الشارات الحيوية عن طريق مجسات بيوطبية. اما عن النظام الفرعي الثاني، فهو يتكفل بالمعاجات الإضافية للإحداثيات التي تبعث عند الطلب من الجهاز المتحرك. هذه الإحداثيات التى وقع معالجتها يتم مراقبتها و تشخيصها عن طريق منظومة تواصل معتمدة على الحاسوب. يتضمن هذا التصميم دراسة للتقليص من استهلاك الطاقة و التقليل من تكلفة التصنيع بالاظافة الى امكانيات تحديث متقدمة. هذه المقالة تسرع في تقارب التكنلوجيا الرقمية مع مجال تكنلوجيا الرعاية الصحية.

الكلمات المفتاحية: الشارات الحيوية، تقنية الزيكبي، رعاية ذاتية للصحة، تصميم متكيف، ارسال موثوق وآمن المعلومات.

Abstract: Nowadays, there is a significant improvement in technology regarding healthcare. Real-time monitoring systems improve the quality of life of patients as well as the performance of hospitals and healthcare centers. In this paper, we present an implementation of a designed framework of a telemetry system using ZigBee technology for automatic and real-time monitoring of Biomedical signals. These signals are collected and processed using 2-tiered subsystems. The first subsystem is the mobile device which is carried on the body and runs a number of biosensors. The second subsystem performs further processing by a local base station using the raw data which is transmitted on-request by the mobile device. The processed data as well as its analysis are then continuously monitored and diagnosed through a human-machine interface. The system should possess low power consumption, low cost and advanced configuration possibilities. This paper accelerates the digital convergence age through continual research and development of technologies related to healthcare.

Keywords: Vital signs, ZigBee, Autonomous healthcare, Adaptive architecture, Reliable and secure data transmitssion

1. Introduction

Numerous wireless personal area network (WPAN) technologies have grown significantly fuelling the interest for applications such as health monitoring, smart homes, and industrial control. ZigBee is the first industrial standard WPAN technology that provides short-range, low-power, and secured communication (ZigBee Alliance Document, 2004). Also, it supports mesh networking and multi-hopping. It is a new wireless network protocol stack of IEEE 802.15.4 for use in industrial equipment and home appliances in order to take in multi-type, multi-point sensor information (Hidetoshi and Hiroaki, 2006). While many smart home application areas such as lighting, security, and climate control have been suggested using the ZigBee

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*Corresponding author's e-mail: lazhar@squ.edu.om standard, health-care applications have not received much attention despite their importance and high-value added.

One of the most promising applications of sensor networks is for human health monitoring (Farshchi, *et al*. 2006). A number of tiny wireless sensors, strategically placed on the human body, create a wireless body area network that can monitor various vital signs, providing real-time feedback to the user and medical personnel. The wireless body area networks promise to revolutionize health monitoring. However, designers of such systems face a number of challenging tasks, as they need to address often quite conflicting requirements for size, operating time, precision, and reliability.

A biotelemetry system is in fact one type of telemetry systems where the desired data which is to be collected is a living organism's basic physiological functions. Such data would be body temperature, blood pressure, heart rate, electrocardiogram (ECG) and electroencephalogram (EEG) (Kang *et al*. 2006).

Monitoring by telemetry has some advantages over traditional monitoring especially for patients who do not have to stay in their beds but nevertheless must be monitored continuously. It improves the quality of life of patients, doctor-patient efficiency, decreases patient discomfort and extends the reach of health care. Traditionally, the sensors along with the monitoring unit are attached to the patient by wires which results in restricting the movement of the patient. In addition, whenever the patient needs to be moved, all monitoring devices have to be moved as well, which means they should be disconnected and then reconnected. This brings overheads, time consumption and job redundancy.

Our aim is to develop a reliable multipurpose prototype solution of a wireless communication system for real-time biosignals monitoring with secure transmission capability. This solution should provide all the above-mentioned functionalities to prove the feasibility of the integration of the whole system in a compact system-on-chip (SOC) (Jovanov *et al*. 2000; Toral *et al*. 2001 and Bracke *et al*. 2007). With such a generic fully programmable IC, the cost-effective development of biomedical devices for different applications in the field of homecare and emergency comes within reach (Van Helleputte *et al* . 2007). In the first phase, we describe both the implementation of the acquisition prototype with wireless transmission capability (short-range ZigBee module); and the tool of real-time acquisition, processing, storage and visualization in the base station unit.

The outline of this paper is as follows: section 2 describes the system overall architecture and design. In section 3, we describe the system co-design and implementation. Experimental results and final prototype are described in section 4, while section 5 concludes the paper.

2. System Overall Architecture and Design

2.1 System Analysis

The proposed design has many interesting technical features such as large versatility (Micro-controller embedded system), efficient power management (power saving technique), pulsed measurement mode concept, embedded interface with a dot matrix sensors (front-end), on request addressable sensor node (polling mode), selectable data refreshment time, in-situ wireless data programming and upgrading (boot-loader technique), bidirectional data link (half duplex with reverse telemetry).

A ZigBee RF Module has been selected to meet IEEE 802.15.4 standards and the ISM 2.4 GHz frequency band. XBee RF Module complies with Part 15 of the FCC rules and regulations (Product Manual v1.xAx by MaxStream, Inc.). It supports the unique need of low-cost, low-power wireless sensor networks. The module requires minimal power and provides reliable delivery of data between devices. It is a short range technology that allows secure and robust communications. The use of radio device, capable to transfer data over a range of up to 100 meters outdoor-line of sight and up to 30 meters indoor-urban, is well recommended.

As user interface, a windows API (Application Programming Interface) application was developed with high level design software for graphical user interface development.

The overriding challenge in developing such a biotelemetry system is to keep it small in size and economical in energy consumption but with a high flexibility in terms of various measurement types as well as the ease of use. To overcome these constraints a basic architecture has been designed, with an embedded MCU core which is not variable (hardware architecture) in all measurement types.

The block diagram of the designed system is shown in Fig.1 as a prototype. It consists of two main parts: the patient side (upper part of Fig.1) and the Testbed's side (lower part of Fig. 1).

2.2 Patient Side: Sensors and Signal Conditioning

The designed architecture has the minimum requisites of an autonomous system: a dot matrix multi-sensors array, an intelligent power saving and supervision, an embedded microcontroller and a serial communications block for the two-way transmission of data (full-duplex) through a ZigBee RF transceiver module. The

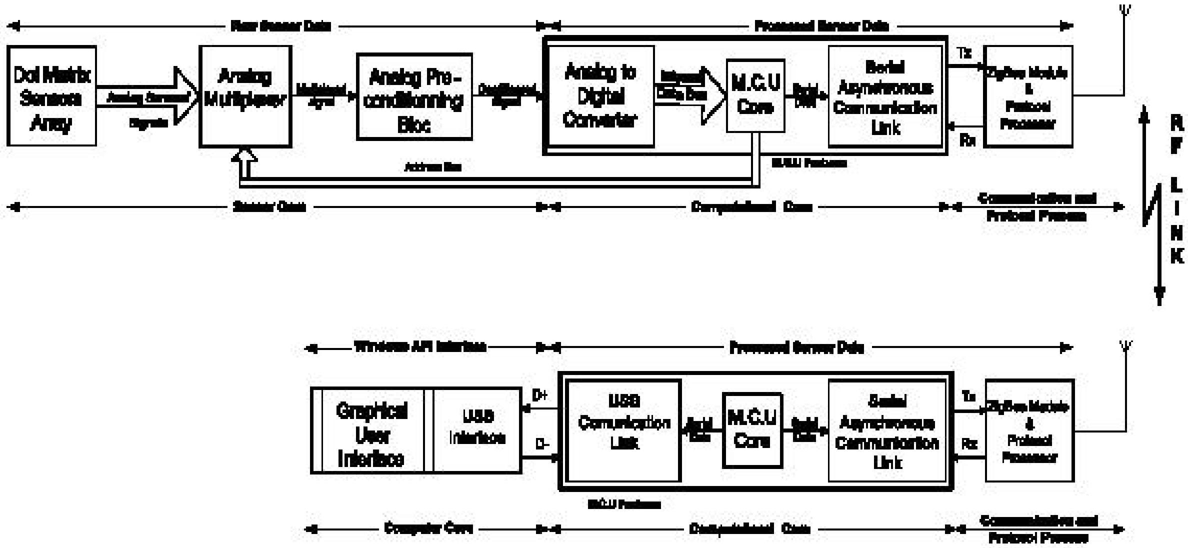


Figure 1. Overall block diagram of the acquiring chain

latter allows the MCU to receive instructions, memory program upgrade and gather information from requested sensors (polling mode).

Microchip's PIC18F4550 Microcontroller is selected because it has an On-chip FLASH Program Memory with In-System Programming (ISP) which makes it flexible and easy to upgrade. It is an 8-bit RISC (Reduced Instruction Set Computer) circuit with 8 ADC converters, 3 timers, serial UART (Universal Asynchronous Receiver Transmitter) and an enhanced USB interface working with a clock frequency up to 20 MHz. Its internally implemented RISC architecture gives an instruction runtime between 80 and 200 ns depending on the chosen oscillator.

The dot matrix sensors array contains several sensors, which can sense one or more physical quantities. The addressable sensor interface chip provides the address, the amplification and analog-to-digital conversion of the sensed signal. It contains an analog multiplexer, a programmable analog front-end and a ten bits analog to digital converter. It makes the sensor interface chip a versatile component, which can be programmed at any time. It offers also, options for intelligent power management. Indeed, all channels which are not in use can be switched off individually. Thus, the microcontroller is dealing with the following tasks:

It controls the sensor interface chip and provides its settings, such as the configuration of the readout electronics like sensor address and analog front-end configuration as well as sensor-specific software routines.

It gathers the data coming from the sensor interface chip and stores it in a memory.

It implements some smart compression algorithms (base-band coder/decoder) to reduce the energy consumption during data transmission.

The bi-directional communication link sends the sensor's data to the transceiver and provides the microcontroller with new programming instructions. Hence, the accuracy, the sensitivity, the acquisition rate and the data processing can be changed during operation, which are necessary to adapt the system to the environment changes and to compensate for drift phenomena.

2.3 Testbed's Prototype

The prototype performs all functionalities fixed above and consists of the Graphical User Interface (GUI), USB interface, Microcontroller and ZigBee RF Module.

The GUI is a windows tool with a user interface that performs dialogue with the patient side subsystem and offers a number of functionalities, such as signal reception, visualization and storage.

The heart of the Testbed is a microcontroller unit MCU, which provides stored program control and data handling and wireless bidirectional serial communication. A PIC18F4550 is used as the same one embedded in the patient side. It allows the communication and the collection of sensed data from the MCU in half-duplex mode. Furthermore, it establishes communication as a bridge-link (gateway) between the PC's GUI interface and the Testbed via USB port.

The communication between the patient side subsystem and the Testbed's sub-system is achieved via a serial channel needing only the Tx/Rx lines which are wirelessly transmitted.

Compared to previous designed systems in literature (Bracke et al and Van Helleputte *et al*. 2007), the proposed architecture presents some significant advanced features such as: (1) an optimized read-out architecture for multi-channel subsystem (single conditioning bloc for all distributed sensors), (2) a windows API graphical user interface, (3) a wide range of programmable parameters (sensor category, sampling frequency, data transfer bit rate, etc.), (4) a real-time physiological signals monitoring with selectable mode (continuous, single and polling mode), etc (Bracke, 2007; Van Helleputte *et al*. 2007; Jinwen *et al*. 2006 and Reid R. Harrison *et al*. 2007).

3. System Co-Design and Implementation

The software development can be divided into two levels:

1. Low level software associated to the microcontroller.
2. High level software for the applications in the Base-Station (Graphical User Interface).

3.1 Firmware Implementation (MCU)

The communication protocol between the external unit (Testbed's subsystem) and the internal unit (patient subsystem) can be depicted by the flow charts illustrated in Fig. 2 and Fig. 3. Both microcontrollers' programs have been structured into two parts as shown in Fig. 4:

1. Main program: It configures the MCU settings and stands-by waiting for interrupt event.
2. Interrupt subroutine: It is a program that runs only when an interrupt event is arrived. Hence, it is not usually activated and is brought into action only by a predetermined interrupt event.

The Testbed's MCU is the main component of the whole acquiring chain. Indeed, it has two interrupt vectors as shown in Fig. 2:

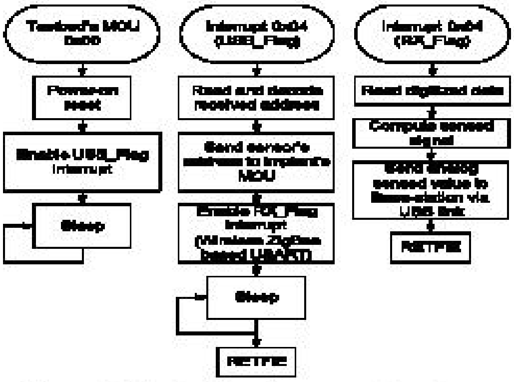


Figure 2. Testbed's subsystem flow chart

1. One interrupt enabled when receiving an instruction from the base station through its incorporated USB interface,
2. Another one enabled when receiving sensed data wirelessly from the implant's MCU through its wireless ZigBee based USART.

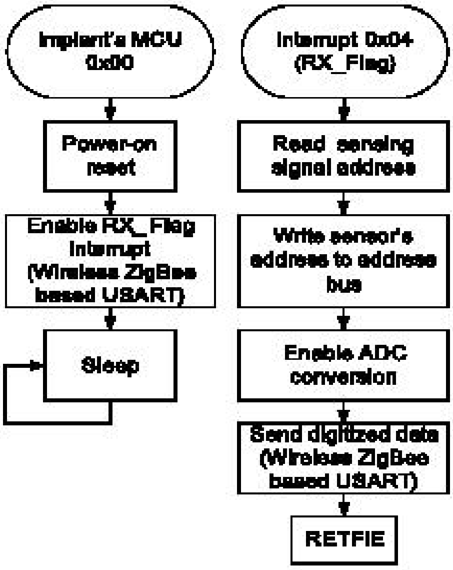


Figure 3. Patient subsystem flow chart

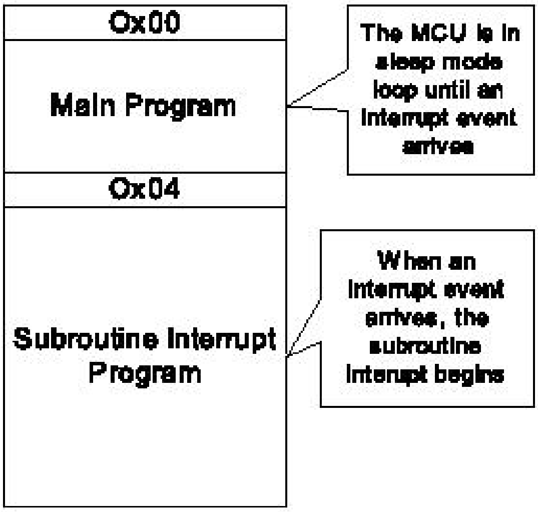


Figure 4. Cartography of microcontroller's program memory

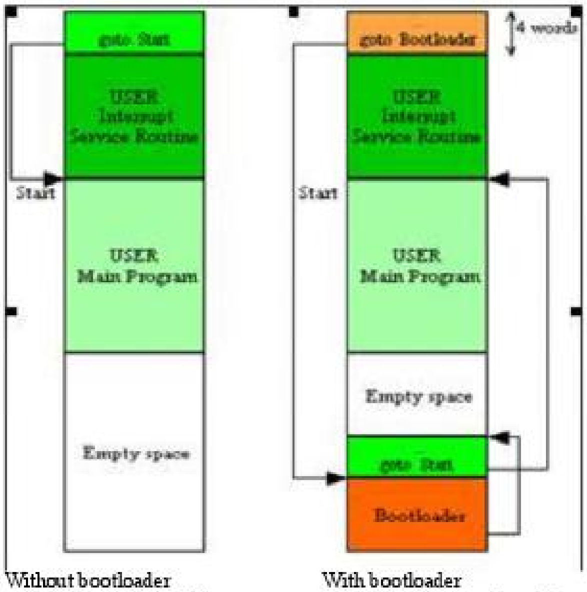
Once data flow is received from the implant's MCU, the Testbed's MCU starts executing the data storage, computing and transmitting to the base station before standing-by then once again waiting for another acquisition request.

The patient subsystem's MCU has minimum tasks to run. In fact, these tasks are limited at standing-by waiting for an interrupt sent wirelessly by the Testbed's MCU through its USART. Once the instructions are received the implant's MCU decodes the next incoming eight bits; sends them to the address bus (to multiplex the requested sensor); and gathers the digitized-recorded data for being sent to the outside (polling mode) and stands-by again waiting for another request.

As we can note, the Patient subsystem's MCU has a limited number of executed instructions which reduces power consumption. To save power further the MCU's running time is minimized which reduced, in consequence, the power consumption. The crucial idea is to refine the firmware implemented into the MCU to perform the Patient subsystem's flow chart depicted in Fig. 3.

Once the firmware is optimized under co-design CAD Tools, its implementation is performed. Based on bootloader technique, one major advantage of our system is the wireless upgrade memory program of the patient subsystem's MCU (wireless bootloader programming) and the testbed's MCU (wired bootloader programming).

Figure 5 shows the program memory cartography comparison of the classic technique and the bootloader technique of firmware implementation methodologies. In order to launch the bootloader after each reset, a "goto bootloader" instruction must exist within the first 4 instructions. Hence, when the MCU starts-up, it boots to the bootloader code incorporated in the program memory and fetches whether an upgrading firmware is waiting for implementation or not. This fetch task takes roughly 30 seconds at each start-up and directly the program counter (PC) jumps to the user main program.



Without bootloader
user code is in colored in green

With bootloader
bootloadercode is colored in red

Figure 5. Program memory cartography comparision of the firmware implementation methodologies

3.2 *GUI Interface: Software Program and Monitoring*

The implemented GUI Interface monitors the acquired signals, receives the data, visualizes and stores them when it is required. The application is developed under LabVIEW platform with the following functionalities:

- Communication with Testbed board via USB port.
- Real-time signal acquisition.
- Signal visualization.
- Data storage.

4. Experimental Results and Discussion

4.1 *Evaluation Prototypes*

According to the system architecture mentioned before, the specifications of all blocks can be determined by the requirement in healthcare monitoring system. Our target here is mainly to show the functionality of such designed telemetry system rather than the optimization in different aspects to be aligned with the biomedical applications (in terms of type of sensors, circuit size and post processing at the Testbed subsystem). We developed a multi-purpose acquiring chain, (see Fig. 6), with the following features,

- Selectable power supply source: Bus power (USB/RS232) or external power.
- True 5V/3.3V CMOS compatible drive output and TTL input.
- Selectable communication port interface: USB, parallel or serial port (FT232RL/FT245RL).
- Full compatible microcontroller chip: PIC16F877, PIC18F4550 and DsPic30F3011 Microchip' microcontrollers.
- Selectable wireless communication data link (UHF, ZigBee or WiFi RF modules) with microcontroller through analogue transmission gate (CD4066).
- 8 multiplexed channel sampling with 10 bit resolution (CD4051 1/8 analogue multiplexer).
- 10-bit microcontroller enhanced ADC converter.
- Programmable gain amplifier with microcontroller through analogue transmission gate (CD4066).
- Free Direct DLL driver installation.

Drivers for these devices (FT232RL and FT245RL) are provided by FTDI for various operating systems. In this design, a DLL driver for Windows/LabVIEW is used. Since USB provides a single +5 V supply with a current limit up to 500 mA, it is possible to use a USB bus to power both designed prototypes.

The Patient subsystem's prototype was implemented in 9.5cm x 13.5cm, Fig. 6 (left). It consists of the programmable analog front end, the PIC18F4550 microcontroller and the ZigBee wireless module. The conditioning block includes: (1) the pressure (strain gauge), humidity and temperature sensors with respectively 0.85 mV/PSI, 40mV/%RH and 10mV/°C as analog output (we used these sensors for testing purpose of the feasibility of the system), (2) the analog multiplexer (CD4051 1/8 analogue multiplexer) and (3) the rail-to-rail unipolar low power amplifier (MCP6002).

The serial to USB interface and bidirectional wireless communication of the Testbed's evaluation prototype was implemented in 9.5cm x 13.5cm (see Fig. 6). It consists of: (1) the USB-to-serial UART interface (an USB2.0 full speed compatible FT232RL USB to Serial converter chip from FTDI Ltd has been chosen for its compatibility to the USB protocol and availability for Windows XP DLL driver file; furthermore it provides an easy and cost-effective approach to transferring data between peripheral devices and a PC at up to 1 Megabaud), (2) the PIC18F4550 microcontroller and (3) the ZigBee wireless module (www.ftdichip.com).

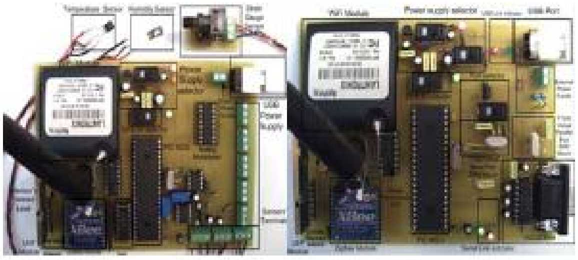


Figure 6. Evaluation board (prototype) patient subsystem's (left) and testbed's (right)

4.2 Experimental Results

Wireless telemetry, USB powering and data transfer, data acquisition and real-time monitoring have been carried out successfully. Figure 7 shows the user interface (man-machine interface) developed under LabVIEW, a visual programming language from National Instruments, allowing easy settings of the Virtual serial port, address sensor and sampling time. The acquired signals are respectively: ambient humidity (Plot 0), ambient pressure (Plot 1) and human body temperature (Plot 2). The signals are recorded during 100 ms and visualized through graphs in real-time.

In order to evaluate the efficiency of the designed acquiring chain, three different sensors were used to measure the temperature, the humidity and the pressure related to the human body and the ambient air. The calibration of the three sensors was done and tested to get accurate measurements. The pressure sensor is calibrated to get ambient atmospheric pressure which is 1 bar, 14.5037744 PSI (Pounds per Square Inch) or 105 Pascal. As shown in the acquiring graph (Fig. 7), the pressure is too near the real value with an accuracy of 1 PSI.

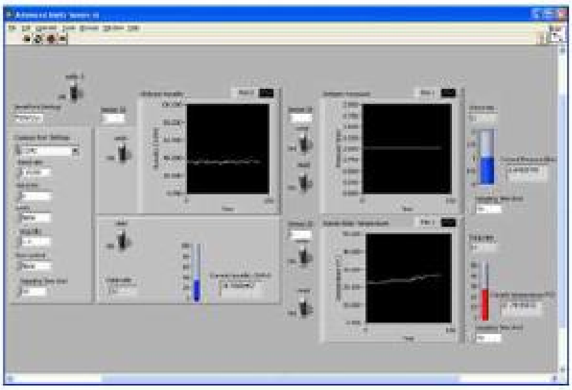


Figure 7. LabVIEW GUI interface

The temperature sensor is adjusted to get ambient temperature and human body heat with accuracy of 0.5°C related to the sensitivity of the chosen sensor.

The humidity sensor is tuned to get ambient humidity with accuracy of 2% RH as sensitivity of the chosen humidity sensor.

The transmission operating range is measured for different transmitting power level as shown in Fig. 8. The power level is varied from 0 dBm to -8dBm through the firmware provided by the ZigBee manufacturer. It is clear that the operating range is basically limited by the sensitivity of the ZigBee receiver and the buildings density (urban compactness).

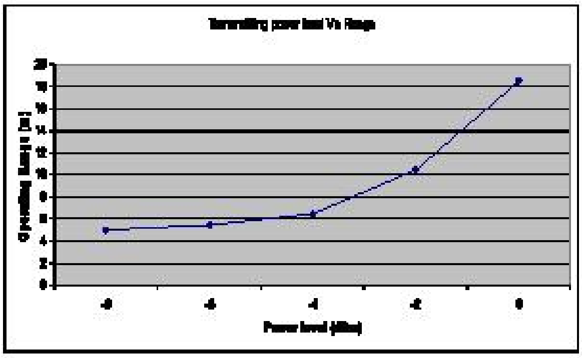


Figure 8. Measured operating distance for different power level

In the prototype system, a test was conducted to evaluate the bit-error rate (BER) performance of the wireless transmission versus the distance and scaled in transmitting power level. The BER indicates the reliability of the channel. For this purpose, 1 Megabits of data were sent continuously from the Patient subsystem to the testbed prototype. A testing algorithm is implemented into the testbed's MCU to check the accuracy of the received bits compared to the randomly sent bits. The BER versus the distance is depicted in

Fig. 9. It can be seen clearly that the error rate increases as the distance increases. This was expected since the transmitted signal is getting weak.

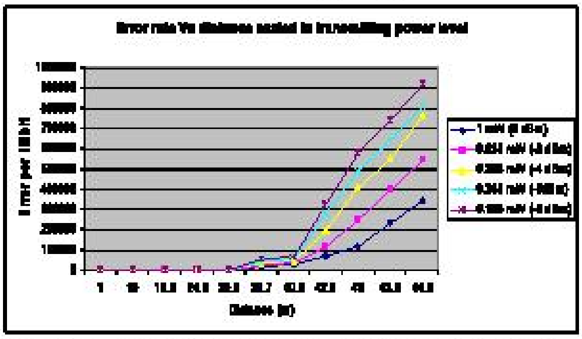
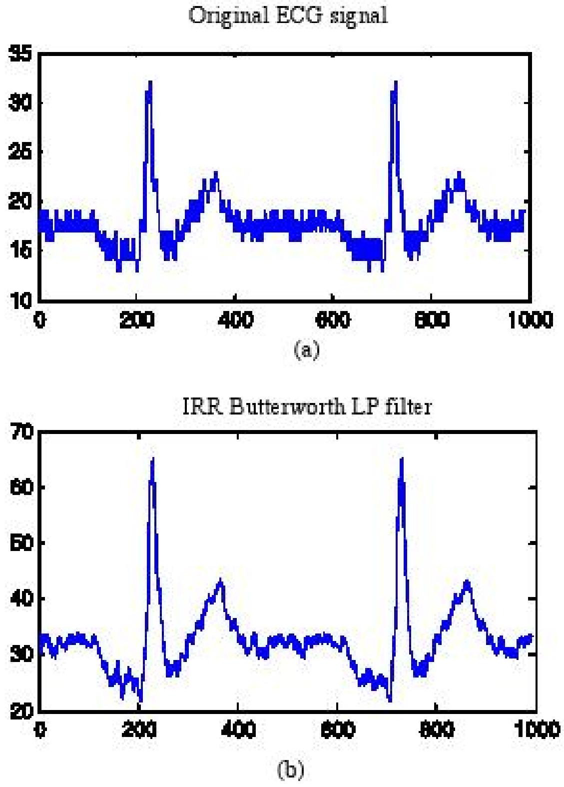


Figure 9. BER measurement Vs distance scaled in transmitting power level


Original ECG signal

(a)

IRR Butterworth LP filter

(b)

Figure 10. Recorded ECG signal (a) original receied signal, (b) filtered signal

As reliability of the channel we can choose an operating range around 5 meters which has a low BER starting from 15.2 to 75.78 per 1Megabits, respectively, to the power level starting from 1mW to 0.158 mW. A power level of 0.251 mW can be affordable with a BER of 65.66 per 1Megabits. The choice of this low power level with such accuracy (low BER) represents a compromise between power consumption and transmission distance.

For the real application, an ECG sensor was used and its relative conditioning block was implemented. After the signal has been received on the PC, it is passed through a series of digital filters to remove noise and further amplify the signal. The waveform in Fig. 10(a) shows the recorded ECG signal for a short transmitting distance (to avoid transmission errors) by our designed telemetry system, while the waveform in Fig. 10(b) shows the signal after amplification and noise removal (the signal passes through an IIR Butterworth lowpass filter). Its P, Q, R, S functions can be used for ECG monitoring application. In-depth design and implementation of post processing algorithms go beyond the scope of this paper, and are left for future work.

Acknowledgments

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Conclusions

This paper describes an implementation of a telemetry monitoring system using ZigBee technologies and embedded system. As the ZigBee was applied to communication for monitoring, available feasibilities are confirmed. The system possesses low power consumption, low cost and advanced configuration possibilities, especially mobility on wiring to remove the limitation of traditional wired biomedical network systems. Its reliability has been measured and demonstrated through experimental results related to the BER measurement. Our future work is to customize the hardware and software to fit the system within the real-world environment as well as to elaborate further in the design and implementation of post processing algorithms.

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