Heart rate wireless monitoring system “CardioBeat”,
novel approach to ECG processing and representation

Vjacheslav E. Antsiperov, Gennady K. Mansurov

Institute of Radio-engineering and Electronics of RAS
Mokhovaya 11-7, Moscow, 125009, Russia
Tel.: + 7 [495] 629-73-82 Fax: +7 [495] 629-36-78 E-mail: antciperov@cplire.ru,

Abstract

This article concerns the development of the heart rate wearable wireless monitoring system “CardioBeat”. This system has two types of transmission mode, which are total signal transmission and heart rate transmission modes. The developed system uses wireless PAN (Personal Area Network), which operates in low-power mode. It is composed of two main parts: ECG registering circuit with wireless communication module and base station with terminal. The registering circuit has three surface electrodes, ECG amplifier and microcontroller. In total signal transmission mode, it can send data with transmission speed corresponding up to 300 ECG samples per second. In heart rate transmission mode, it can calculate heart rate from ECG data with 300 samples per second and send packets at the specified rate. Base station communication unit forwards the received data to PC, where the data can be stored and displayed. The developed equipment showed the possibility of real-time monitoring of the patients in their daily life and is expected to contribute, in particular, to the saving of medical expenses.

Keywords: Heart rate wireless monitoring, ECG processing, 2D graphical representation

1. Introduction

The interest in wearable health systems originates initially from the need to extend health services out of the hospital and monitor patients over extensive periods of time. Intelligent health monitors are integrated systems in contact with the body able to detecting, processing and analyzing the patient’s health conditions – and even carry out actions if necessary. Research and development in such area is mainly driven by two different, but complementary, approaches. The first one is “application-pull”, stemming from an increased user demand for new solutions in healthcare. The second one is “technology-push”, in which technological innovations lead to new systems and products for healthcare solutions. In both approaches, inter-disciplinarity is a key issue. Synergies across multiple domains like Digital Signal Processing (DSP), Intelligent Radio Engineering (IRE) and Information and Communication Technologies (ICT), enable new approaches to support personal health and well-being.

This report presents the state-of-the-art on wearable heart rate wireless monitoring system “CardioBeat”, outlines current research achievements and indicates research trends and challenges in line with two above approaches. The “technology-push” approach is presented in first part of the report and unveils our developing strategy that combines the simplest circuit and compound digital processing. The questions of controlling the wireless communication unit, exactly the XBee module which composes Personal Area Network (PAN) and implements the data wireless communication, are in the highlight. The novel “application-pull” approach that involves the developed new ECG processing method and its results graphical representation is discussed in the second part of the report presented.
2. HARDWARE

Our wearable wireless monitoring system “CardioBeat” essentially exploits ZigBee communication technology and showcases the potential of wireless sensor networks in healthcare by demonstrating the integration of an ECG detect circuit with a XBee modules to allow the wireless transmission of continuous cardiac rhythms or ECG signal themselves, depending on transmission mode selected. Data obtained could ultimately be received by desktop PC or other wireless-enabled device in a multitude of healthcare scenarios. So, in terms of system architecture, CardioBeat is composed of two main parts: measurement module which includes ECG detection circuit with wireless communication XBee module and base station which is PC networked with another XBee. Fig. 1 shows the CardioBeat system design and how a measurement module attaches to a patient.

![Fig. 1. CardioBeat design. A - measurement module, B – cardio (holter) electrodes, C - base station communication module](image)

ECG, served as the most significant physical parameter, not only reflects the cardiac function of human beings but also includes other information about human health conditions. For the ECG signals, its range is about $10 \mu V$ to $5 mV$ and frequency range is between 0.05 Hz to 100Hz. In the detection course, the EEG, respiration signals and other noises will decrease the signal noise ratio (SNR) of the system, even worse the ECG will be submerged completely. In order to solve the problem mentioned above and make the detection circuit as simple as possible, the improved electrode system, which only has three electrodes (holter), is introduced in the device. The signals of electrodes I and II are available and can match the needs of monitoring, which pays much attention to the heart rate and R wave. The detection circuit of ECG, which should have the advantages of high input impedance and high CMRR, is mainly composed of four parts, including preamp, band pass filter, notch filter and main amp. Due to the frequency range of R wave, the two-order Butterworth filter with cut frequency of 160 Hz is used in the circuit and the gain of the whole circuit is about 650. The acquired signals will be transferred to digital signals in MCU after preprocessing and sent to the base station wirelessly via XBee. The schematic of the analog circuit is shown in Fig. 2 (left).
Detection analog circuit board is pictured in Fig. 2 (right) in a circle; three separate patient electrodes exits on the top of the photograph. The circuit is intended to take readings from these electrodes and deliver the resulting trace to the MCU’s built-in ADC. MCU, after appropriate digital processing of the data received, transmits the results via XBee module to the base station according to the specified scenario.

We choose XBee module based wireless communication technology by the reason of some its attractive features which are suitable for medical service domain. XBee RF Modules were engineered by Digi International Inc. to meet IEEE 802.15.4 standards and support the unique needs of low-cost, low-power wireless sensor networks. The modules require minimal power and provide reliable delivery of data between devices. The modules operate within the ISM 2.4 GHz frequency band. Some XBee key characteristics are outlined in the following Table 1:

<table>
<thead>
<tr>
<th>feature</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor/Urban range</td>
<td>up to 100’ (30 m)</td>
</tr>
<tr>
<td>Outdoor line-of-sight range</td>
<td>up to 300’ (100 m)</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>1 mW (0 dBm)</td>
</tr>
<tr>
<td>Receiver Sensitivity</td>
<td>-92 dBm</td>
</tr>
<tr>
<td>TX Current</td>
<td>45 mA (3.3 V)</td>
</tr>
<tr>
<td>RX Current</td>
<td>50 mA (3.3 V)</td>
</tr>
<tr>
<td>Power-down Current</td>
<td>&lt; 10 μA</td>
</tr>
</tbody>
</table>

Measurement module is fully controlled by MCU (in this time ATmega64L). Module is powered by 3 volts (2 batteries AA size) and contains no voltage converter. Software of MCU can be upgraded and in-circuit loaded (possibly through air). The MCU interfaces to XBee RF Module through a logic-level asynchronous serial port. XBee RF Modules operate in Transparent Mode and API (Application Programming Interface) Operation Mode. When operating in Transparent Mode, the RF module acts as a serial line replacement - all UART data received is queued up for RF transmission. When RF data is received, the data is sent out to MCU. Frame-based API extends the level to which a host application can interact with the networking capabilities of the module. All data entering and leaving the module is contained in frames that define operations or events within the module. Application sends data frames to the RF module that contain address and payload information. The module sends data frames to the application containing status packets; as well as source, received signal strength indicator and payload information from received data packets. Module can receive commands from the base station to change settings (sample rate, configuration, sleep period etc.).
2. SOFTWARE

Our wearable wireless monitoring system “CardioBeat” has two types of transmission mode (scenarios), which are total signal transmission and heart rate transmission modes. In the case of signal transmission the ECG data acquired by measurement module will be simply sent to the base station in wireless way for further modification and analysis. The base station acquires the data from patient and displayed in the terminal. In the meanwhile, the results will be stored properly in the database so that the patient can easily find out his historical records over the future. Within the bounds of such scenario we can programmatically set a number of operating parameters: sampling rate, recording duration, transfer rate, etc.

The heart rate transmission scenario is more complicated. Roughly speaking it reminds a well-known holter monitoring. The last gives somebody a constant reading of patient heart rate and rhythm over a 24-hour period (or longer). Its extended recording period is sometimes useful for observing occasional cardiac arrhythmias that would be difficult to identify in a shorter period of time. The main approach of data compression and diagnostics in holter monitoring is based on analyzing the statistics of the R-R intervals.

Traditionally R-R interval estimates are obtained by direct processing of ECG waveforms, namely, determining the series of consecutive minima and maxima and finding the maxima, which occur after a long ascent and are followed by a long descent etc. Such measurements are much subjected to different kinds of distortions: baseline drifts, jitterbug noise, interference induction. Instead of that we have developed another approach to the problem of R-R interval measuring – Multiscale Correlation Analysis (MCA) [1] - which is very robust end effective for this aim.

The core of MCA is the analysis of short cross-correlation function (CCF) parameters dynamics, namely the time location and the value of CCF side. It was shown that the dynamics of CCF side peak has faithful interpretation in terms of signal local quasi-periodicity and in high quasi-periodical segments the side peak time location is hardly related with the signal period value. Initially CCFs were formed by windows with signal-defined but fixed size. Further it was found that better and complete results can be obtained with using a set of window sizes or scales, i.e. when common correlative approach was transformed into multiscale one. But in this case we face the problem of abundant number of parameters – current time, window size, time lag and therefore the problem of comfortable representation. The way out was found in wavelet theory. An advantage of wavelet transforms is that the windows vary: they are short for high-frequency components and long for low-frequency ones. In view of inverse proportionality of signal frequency and its time period, the same idea in the time-and-time domain would look like as follows: windows must be short for small time lags and long enough for larger lags.

Taking into account above observations about window sizes, it remains to decide the last question – how windows compared must be disposed in reference to each other and with respect to the current time moment concerned. For the approach under discussion we deposit data windows symmetrically with respect to current time \( t \) and adjacent with each other, i.e. without overlapping. As a measure \( r(t, \vartheta) \) of the signal quasi-periodicity we accept the scalar product of normalized versions of the left and right with respect to current time moment data windowed:

\[
r(t, \vartheta) = \frac{\int G^2 (2t', \vartheta)x(t'+t - \vartheta/2)x(t'+t + \vartheta/2)dt'}{\sqrt{\int G^2 (2t', \vartheta)x^2(t'+t - \vartheta/2)dt'} \sqrt{\int G^2 (2t', \vartheta)x^2(t'+t + \vartheta/2)dt'}},
\]

where \( x(t) \) - ECG signal, \( G(t) \) - window, \( t \) and \( \vartheta \) - current time and scale.

From mathematically accurate analysis of \( r(t, \vartheta) \) it follows that the there always are unity maximum on \( t \) axis ( \( \vartheta =0 \)). In the case of strictly periodic signal \( x(t) \) it is also true for
\[ \vartheta = \pm T, \pm 2T, \ldots, \] where \( T \) is a period. Therefore, a characteristic property of a strictly periodic signal is the presence of unity-value maxima recurring with the signal period. In the absence of a strict periodicity, i.e. in the case of quasi-periodic signal like ECG the high order maxima are less than unity but still exist. So for the time moments within the quasi-periodic intervals we will have characteristic linear pictures, in the absence of quasi-periodicity – irregular picture filling. Two typical 2-D graphical representations for a measure \( r(t, \vartheta) \) of ECG signals are shown in Fig. 3.

![2-D graphical representations for ECG. A – normal sinus rhythm, B – supraventricular tachyarrhythmia](image)

Discussed above MCA approach was realized in algorithm of R-R interval estimation (and its regular dynamics blackouts detection). The fast form of algorithm makes it possible to process ECG in real time and transmit results at the specified rate. CardioBeat system tests have shown that this approach really satisfies reliability requirements and finds out the solution of the problem.

5. Conclusion

From the results above, we can easily see that the new wearable wireless monitoring system “CardioBeat” has already reached the goals we expect. The traditional ECG monitor will give way to the new generation systems based on wireless communication technology. With the help of the wearable wireless monitor, both efficiency and quality of medical care can be greatly improved. In the near future, the application is intended to expand from lab to the wide community, even to the homecare.

References
