A bi-phase enabled serial acquisition system for remote processing of digitized ECG

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Abstract

This paper presents an approach for acquiring digitized ECG samples in a personal computer using an offline communication technique. For this, two standalone embedded modules are placed at the two ends of the communication link. The transmit end module collects ECG samples from the source and stores them in a RAM. Finally it converts each data byte into a bi-phase encoded bit stream for transmission using a standard telephone set through post office telephone line. The receive-end module, coupled with the telephone receiver decodes the ECG data, and then delivers them to a desktop computer through the serial port. An application software in the computer is used to store these samples for visual inspection. The detailed architecture and test results are discussed with synthetic ECG data available from PTB diagnostic ECG database (ptb-db) under Physionet.

1. Introduction

Electrocardiograph (ECG) is one of the important physiological signals for cardiac investigation. Considering its importance and growth of cardiovascular diseases (CVD) all over the world for the last three decades, ECG has been one of the thrust areas of research by the medical science and technology community. Presently, popular method of ECG investigation involves visual inspection of 12-lead ECG recording by a physician. A typical ECG measurement system consists of ECG lead system, analog signal conditioner, switching arrangement for channel selection, plotting mechanism with strip chart paper. ECG readout circuits assume special significance in a typical ECG acquisition and processing system. The low amplitude (±5 mV) ECG signals picked-up from different leads include various noise signals like motion artifacts, baseline wandering, EMG (Electromyogram) noises etc. Normally a high CMRR instrumentation amplifier (IA) in conjunction with a filter bank is used for amplifying the ECG signal, rejecting some noises [1,2]. Some popular configurations of IA used for the purpose is reported [3–5].

Biotelemetry, a special branch of Biomedical Instrumentation, deals with transmission of physiological data to a remote location that has the ability to store, interpret and decide on the subject (normally human). Remote ECG monitoring is currently practiced by health care service agencies, military, sports medicine personnel, space research organizations and many more. The first work on ECG transmission was done by W. Einthoven, who transmitted the ECG signal over telephone line from nearest hospital to his laboratory.

For remote communication of ECG this technique was adopted and continued for many years by scientists. With the advancement of information and communication technology, there is a rapid change in terms of implementing newer methodology, with increase in reliability, accuracy, protection from interference effects etc. The first step towards this shift is digitization of the ECG signal itself and introduction of personal computer (PC) in data communication and processing [6–8].

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With the advent of miniature, low-power integrated circuit technology, portable devices are available in different form to transfer ECG or other physiological data from a patient to a distant location [9–11]. This enabled scientists and health-care professionals with remote monitoring of patients at home using portable gadgets and computer based systems. At present public communication networks like GSM, internets are increasingly being used for patient healthcare services for transmission of patients’ physiological data. In some applications, cellular handsets and PDA with powerful software are used to directly collect the patient’s ECG and transmit it to the physician or remote station for monitoring [12–14]. Embedded system applications are playing a significant role in all such applications, where the medium access control (MAC) layer of the network is being controlled by the microcontrollers [15,16].

In this paper, a method of acquisition of ECG signal into a remote PC is presented. An offline communication technique is utilized to transmit a short duration of ECG data using bi-phase encoding technique with the help of a telephone line. Two standalone embedded systems are developed to achieve this. The first one is for acquisition, temporary storage and encoding of ECG data at transmit end. The other one is at receiving end for decoding of received bit stream and delivery to a PC. An application software is used for storage of ECG data using a graphical user interface (GUI) based front panel toolsets. A graphical plot is also generated for visual inspection by a receive end physician. The performance of system components are described with PTB-diagnostic ECG data (ptb-db) from Physionet.

2. Materials and methods

The developed system for ECG signal acquisition and storage consists of the following modules. The block schematic of the entire system is shown in Fig. 1.

2.1. Analog ECG acquisition and transmitter unit (local site)

The objective of this unit is to acquire the ECG signal from the source and then initiate for an offline transmission. In this work, the ECG signal is simulated by an arbitrary waveform generator (AWG) fed with single lead ptb-db data.

First, the analog synthetic ECG is amplified suitably by a low-offset high CMRR instrumentation amplifier to a level of ±2.5 V before digitization. To avoid negative half of the ECG, a +2.5 V dc offset is added at the input of ADC after amplification. The single channel 8-bit ADC is sampled at a rate of 1 kHz by the standalone embedded system, (named TES or, Transmit-end Embedded System) which stores the digitized samples in a 32 kB on-board RAM before transmission. Next, the MCU of the TES converts the stored data to a bi-phase modulated base-band signal in two distinct frequencies 800 Hz (for ‘1’) and 400 Hz (for ‘0’) to transmit through a normal telephone set. This signal is applied at the ‘MIC’ input after proper level adjustment. In this work Atmel 89C51 is used for simple instruction set and easy interfacing support of external RAM.

In a bi-phase modulation (BPM) scheme, as shown in the Fig. 2, the output bit always toggles its state after a fixed interval of time. This interval of time, in other words, determines the bit width of the output bit. Again, depending on the input data bit status, the output level may toggle once in the middle of the bit-width interval. If the input bit is ‘1’, the output undergoes one state transition at the middle of that interval, while for ‘0’ bit, there is no such transition. This implies that the frequency to represent a ‘1’ bit is exactly double to that of ‘0’ bit. So, in general a bi-phase modulation is a special type of frequency shift keying (FSK) modulation. For successive occurrence of same bit at input, there will be a state transition between two intervals at the output. By this way, during transmission dc like nature of the original ADC output, which may occur due to successive ‘0’ or ‘1’ bits, is avoided, instead a continuous time varying signal is generated. Without this BPM scheme, the transmission may be full of error as there are situations where successive ‘0’ or ‘1’ bit may occur at the ADC output. This DC like behaviour of the signal can’t be communicated using MIC input of telephone set.

The schematic flow-chart of the TES for generating bi-phase modulated ECG data is shown in Fig. 3a. At first, by user command, 32 kB ECG samples are collected and stored sequentially in RAM. Then, by another user command, each stored byte is converted to corresponding bi-phase formatted signal data for sending to the MIC input of the telephone line. Each encoded byte is prefixed with a low (logic 0) ‘start’ bit and a high (logic 1) stop bit to form a 10 byte frame. To keep synchronization between the transmitter and receiver, a fixed byte (FFH) is used as header at the beginning of each data packet.
2.2. Receiver unit with PC for online acquisition and storage (remote end)

As shown in Fig. 1, the receiver module is based on another embedded system, (named RES or, receiving-end embedded system) which receives and decodes the bi-phase encoded data. The analog signal coming out at the earphone terminal of the telephone receiver is the demodulated bi-phase encoded signal. At first, it is converted to an equivalent binary stream by suitable wave shaping circuit and then fed to the RES MCU (Atmel 89C2051). The logic flowchart for reconstruction of the data bytes from encoded bi-phase signal is shown in Fig. 3b. Decoding of the incoming bit stream is performed on the basis

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**Fig. 3.** Flowchart schematic for (a) TES and (b) RES module.
of a comparison with a reference bit width. So, a zero bit is decoded from a ‘wider’ pulse and a one bit is decoded from two consecutive ‘narrower’ pulses. At first, the RES MCU attains the synchronization by locating the header pattern in the incoming data. The decoded bytes, only after the header is found, are taken as valid data. ‘Start’ and ‘Stop’ bits are selectively discarded. Each such reconstructed byte, representing an ECG sample are converted to a RS232 formatted data by the RES MCU for online delivery to the PC at 9.6 kbps. Final data storage and display of the ECG is performed using a MATLAB-based application software. A GUI is provided which enables a semi-skilled professional to invoke commands using icon-based tool-sets like axes, menus and push-buttons to control the operation of the PC-based system.

The application software is developed for automatic storage of incoming data stream at its serial port through ‘event-driven’ programming. First, a predefined number of data bytes are stored in a temporary text file. For further storage of this ECG data in original mV value to facilitate signal processing, a conversion operation is executed using a separate icon-based tool, by which a separate file is created.

The conversion formula is given as,

$$\text{Analog} \ (\text{mV}) = \frac{[\text{Digital value} \ (D) - \text{digital equivalent of bias voltage}]}{\text{Total amplification achieved in amplifiers}} \times 19.6$$

As evident from the formula, the conversion factor is a function of gain factor of the instrumentation amplifier circuit, dc offset provided at input of the ADC, and resolution of the ADC.

3. Testing and results

The functions of different blocks of the entire system are separately tested, before they are being coupled. For testing purpose, synthetic ECG data has been used from PTB diagnostic ECG database (ptb-db) under PhysioNet [17]. The data files are available in Physiobank under Physionet, and offers digital recordings of physiological signals and related data for use by the biomedical research community. Physiobank currently includes databases of multi-parameter cardiopulmonary, neural, and other biomedical signals from healthy subjects and patients with a variety of conditions with major public health implications, including sudden cardiac death, congestive heart failure, epilepsy, gait disorders, sleep apnea, and aging. PTB, the National Metrology Institute of Germany, has provided this compilation of digitized ECGs for research, algorithmic benchmarking or teaching purposes to the users of PhysioNet. The ECGs were collected from healthy volunteers and patients with different heart diseases.

In this work, the ECG signal is simulated by generating it from an AWG (Model Agilent 33220A) with the help of standard ptb-db file. At first, a precisely cut R–R data points from a single lead ptb-db data file is stored in a text file. These samples are downloaded into the volatile memory of the AWG using Agilent Intuilink waveform editor. The amplitude and frequency setting of the generated ECG is set from the front-panel switches of the AWG. Since the ptb-db file provide a sampling interval of 1 ms, the ADC is sampled at 1 kHz frequency to keep parity between the generated signal and originating database.

Before the transmission link is tested for performance, the ECG signal generated from the AWG is locally acquired and tested for performance. An 8051-based standalone embedded system is developed for collecting the ECG samples and online delivery to a PC through its serial port for storage and analysis [18]. After the faithful reconstruction of the ECG samples are ensured, the TES and the telephone set are tested for performance, at first, without using bi-phase modulation. Here, a known byte pattern (either ‘00’h or ‘FF’h or ‘F0’h or ‘0F’h) is transmitted serially at bit-width equivalent to 400 Hz. For ‘0’ bit the output data line remains logic low (L), and ‘1’ it remains logic high (H) using RS232 format. The output of the telephone receiver and resulting bit stream are shown in Fig. 4. A packet consisting of one synchronization header (‘255’) with eight data bytes (‘00’) is generated as shown in Fig. 4a. The signal status of the TES and same of telephone receiver, as shown in Fig. 4b indicates that receiver generates an inconsistent output, from which the RES MCU fails to correctly extract bit ‘0’ and ‘1’. As a result the system gives erroneous result.

![Fig. 4. Bit pattern generated by TES and telephone receiver without bi-phase encoding.](image-url)
In the next stage, TES and RES are tested with ECG data generated from AWG. The TES is programmed to produce bi-phase signal, with the RES directly coupled bypassing the telephone transceivers. This is to assess the correct extraction of data-bits by the receiver unit from the bi-phase signal generated from the transmitter. After temporary storage of ECG data in on-board RAM, the data packet is formed by one header plus eight bytes of ECG data for transmission. Fig. 5a shows the original ECG signal, its encoded bi-phase formatted serial bit-stream Fig. 5b and the receiver side embedded system performance. Correct detection of header and subsequent data bytes by the receiving end microcontroller is reflected in Fig. 5b and c, respectively.

Finally, the TES and RES units are connected through a telephone line. For selection of encoding frequency, it is observed that the telephone set provides optimum response at 400 Hz and 800 Hz for bit ‘0’ and bit ‘1’, respectively. It is calculated that using these encoding frequencies, the time taken by a data frame (consisting of one start bit, eight data bits, and one
stop bit) for transmission is exactly 12.5 ms. For a data packet consisting of one header plus eight data bytes, the total time taken by the transmitter to complete the 32 kB data transfer would take 7.5 min (approx.), which is also the engagement time between TES and RES units. The extracted data bytes are delivered to the desktop PC from the RES module at a rate of 9.6 kbps, which means, a complete packet conforming RS232 protocol consumes 1041.6 μs to reach the UART of COM port. The programming of the data acquisition software is designed for receiving the incoming bit stream in interrupt mode. Fig. 6 shows the performance of the serial communication between RES MCU and PC with speed of communication fixed at 9.6 kbps. Fig. 6a represents the serial delivery of 4 data packets from the MCU to the PC, with each packet numbered in CRO screenshot. Between two successive packets, exactly 8 bytes are delivered, as revealed by number of interrupts (shown as transitions in upper channel). It also reveals that the MCU selectively transfers only the extracted data bytes to the PC, excluding the header. Fig. 6b shows the packet duration with status of the RS232 link.

The embedded systems layout used in the transmitting end and the receiver end are shown in Fig. 7.

Fig. 8 shows a screen shot of the GUI on the PC where ECG signal after it is stored. The digitized ECG data plot is shown in Fig. 8a along with the temporary data file that is automatically being created after the acquisition at PC. These digitized values are then converted to corresponding ECG samples for storage and future analysis. The data file after re-conversion and plot of analog ECG data is shown in Fig. 8b.

After reconstruction of ECG data, it is checked for reliability. A widely used performance index for checking the merit of reconstruction used in ECG communication is percentage root mean square difference, abbreviated as PRD, given as,

$$\text{PRD} = 100 \times \sqrt{\frac{\sum_{n=1}^{N}(x[n] - \hat{x}[n])^2}{\sum_{n=1}^{N}(x[n])^2}}$$

where, $N$: total number of samples in the data set, $x[n]$: actual value, $\hat{x}[n]$: reconstructed value.

A point to point comparison is performed between two suitably cut R–R points from the generated synthetic ECG acquired from AWG using a DSO using Tektronics Open choice desktop software and after remote acquisition of the ECG samples. Test results with 50 different single lead transmission using the system yield an average PRD level of 2.2%, which is acceptable. The chief sources of error are due to quantization error and communication noises.
4. Conclusion and discussion

This communication describes the suitability of bi-phase modulation for ECG transmission to a remote computer. Salient contributions of the work are developed TES and RES and MATLAB based data acquisition software. The total developmental cost of the prototype modules (TES and RES) is less than USD 60. At present, the emphasis is on testing proper functionalities of the system components and for that, synthetic ECG data available from PTB diagnostic ECG database (ptb-db) is used. No trial on human being has been performed yet since the system is still under development. The system is tested for short distance communication link, with a low error level. In future for long distance communication, error correction schemes would be incorporated. As the transmission process is purely offline, the developed system does not support real-time monitoring of patients. It is also not meant for prolonged recording.

The proposed system can be used for transmission of patient data for periodic check up from district rural healthcare unit in India to a distant centralized location for storage and further automated analysis. The remote healthcare units in India are in poor infrastructural condition and some of them do not have a PC or advanced facilities. The developed TES requires no high end GUI for operation. A semi-skilled operator only need some push button switches to operate the transmit end module. Portability of the TES also provides an opportunity to collect patient ECG and transmit the same if the TES coupled with a customized telephone set. Presently, the system is tested with a single lead data. But, with minor change in TES and RES firmware it can handle multi-lead ECG data.

In future, along with the ECG data some additional patient information like name, age, gender etc would be transmitted for database management for a geographical area. A matrix keyboard would be incorporated with the transmitter-embedded system for entering these additional data.

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