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Original Article

Experimental study of ECG signal transmission system via a coaxial cable line using Duty-Cycle Modulation

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ABSTRACT

This paper presents the first real and well tested prototyping duty cycle modulation (DCM) signal transmission system. The experimented system is applied to the transmission of ECG signals. It consists of an ECG signal acquisition system, a duty cycle modulation transmitter, a coaxial cable transmission medium and finally a simple low-pass filter as receiver. After a brief review of the literature highlighting the interest of this experiment, we analytically developed different parts of the proposed system. The experimental workbench and main results obtained are presented. These yield very good results since in addition to the high quality of ECG signal reconstitution, we manage to eliminate the power line interference induced during transmission. These results experimentally confirm the feasibility as well as new perspectives of using the proposed systems as a simple remote biomedical instrument.

1. Introduction

The electrocardiogram (ECG) is used to diagnose heart rhythm disorders in a patient. Its acquisition and interpretation is a major challenge, particularly in isolated areas with small number of medical specialists. To overcome these difficulties, many technologies have been used for the acquisition and transmission of ECG signals: Fixed telephony [1], Bluetooth [2], Wireless [3-4], Mobile network [5-6] etc. In addition, a relevant transmission difficulty encountered lies in the high sensitivity of ECG signals to noise [7]: power line interference, electrode contact noise, movement artifacts, muscle contraction, baseline drift, instrumentation noise generated by electronic devices, electrosurgical noise. This potential difficulty has motivated the development of local acquisition, processing and interpretation of ECG signals using microcontroller, before retransmission obtained results [1] [3] [5]. The drawbacks in this solution are the presence of diagnostic errors, the limitation of the interpretation by the algorithm performance, as well as the local processing time and cost of the overall solution. Among new technologies that are intended to contribute to the improvement of the medical system, the Duty Cycle Modulator (DCM) is one of the most latest and relevant. It has already proven its great merits in many other fields as summarized in the recent review paper [8], including analog-to-digital conversion [9-10], digital-to-analog conversion [11-13] and power electronics drivers [14-17]. DCM is not new in the field of telemedicine. It has already been the subject of two very conclusive theoretical works on multi-channel acquisition of biological signals [18] and fiber optic transmission of ECG signals [19]. However, pioneering works were conducted in a virtual simulation environment. As an implication, the contribution of this paper is to propose a pioneering experimental ECG signal transmission system using duty cycle modulation.

The remaining of this paper is organized as follows: in section II, tools and methods required for experimental study are presented. Then section III deals with the presentation of the obtained results, and finally, the conclusion of the paper is outlined in section IV.

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2. Tools and methods of experimental study

2.1. Architecture of the system

The block diagram of the proposed transmission system is shown in Fig. 1. This diagram consists of an ECG signal acquisition module based on an AD8232 KIT equipped with three electrodes, an electronic transmitter with duty cycle modulation, a transmission support by coaxial cable, and an electronic receiver for the reconstitution of the ECG signal transmitted by a low-pass filter. Finally, a digital oscilloscope is used as a terminal for graphical monitoring of the signals involved. It is important to mention that the power supply sources of these component modules have been omitted from this diagram for reasons of clarity.

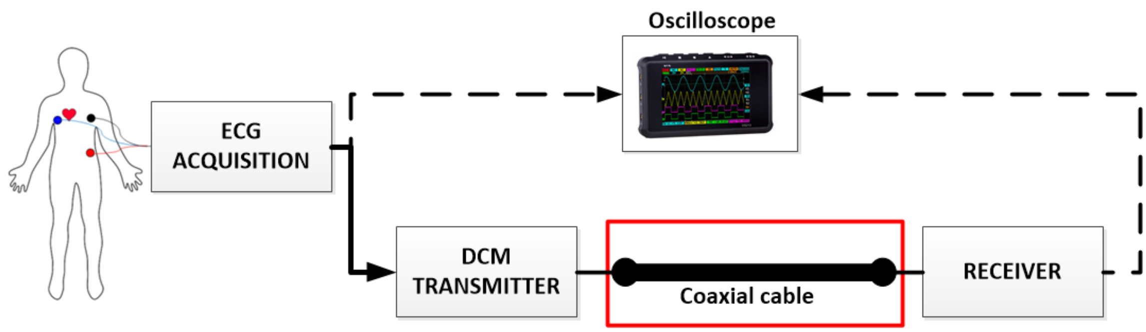


Fig 1. Block diagram of the ECG signal transmission system

2.2 Acquisition of ECG signal

The KIT AD8232, allows to visualize the signal of the electrocardiogram at a very low cost. The main module is the AD8232 board which is an ECG signal conditioning block designed to extract, amplify and filter small bio-potential signals in a noisy environment [20-21]. The AD8232 module operates with 03 electrodes connected in limb shunts: right wrist (R), left wrist (L) and right leg ankle (COM). It is powered by a 3.3V DC voltage source. In our experiment we will use two 1.5V batteries power supply.

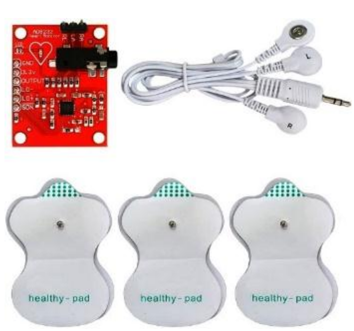


Fig 2. ECG signal acquisition kit AD8232

2.3 Transmitter by Duty cycle modulation

The DCM module in Fig. 3 behaves as a relaxation oscillator controlled by the input ECG modulating signal. The corresponding dynamic model given by equations (1) and (2), and its main characteristics given by equations (3) - (5) have been clearly defined in references [9; 22-24].

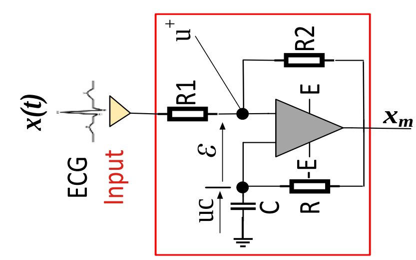


Fig 3. Duty cycle modulator

$$\begin{cases} u^{+}(t) = \alpha x_m(t) + (1-\alpha)x(t) \\ \varepsilon(t) = u^{+}(t) - u_c(t) \\ x_m(t) = E\,\mathrm{sign}(\varepsilon(t)) \\ \dfrac{du_c(t)}{dt} = -\dfrac{1}{\tau}u_c(t) + \dfrac{1}{\tau}x_m(t) \\ x(t) < E \end{cases} \quad (1)$$

$$\alpha = \alpha_1 = 1-\alpha_2 = \frac{R_1}{R_1+R_2}, \tau = RC \quad (2)$$

$$R_m(x(t)) = \frac{T_{on}(x(t))}{T_m(x(t))} \quad (3)$$

$$\mathrm{T}_{on}(x(t)) = \tau \ln\left(\frac{(1-\alpha)x-(1+\alpha)E}{(1-\alpha)x+(\alpha-1)E}\right) \quad (4)$$

$$T_m(x(t)) = \tau \ln\left(\frac{((1-\alpha)x)^2+((1+\alpha)E)^2}{((1-\alpha)x)^2-((\alpha-1)E)^2}\right) \quad (5)$$

The central frequency f_{m0} is obtained for x=0 and expressed analytically from equation (6)

$$f_{m0}(\alpha) = \frac{1}{T_m(0)} = \frac{1}{2\tau \ln\left(\frac{1+\alpha}{1-\alpha}\right)} \quad (6)$$

The transmitter module in Fig. 4 is powered by a symmetrical stabilized source of +5V and -5V. It is subdivided into two parts:

- Duty cycle modulator, consisting of an operational amplifier TL082, and three resistors.
- Operational amplifier follower circuit for impedance matching with the transmission medium.

The transmitter used in this article is realized for a modulation center frequency f_{m0} = 16.4 KHz. Table 1 lists the components used for the transmitter.

Table 1. Components with transmitter values

Components	values
AOP	TL082
R1	10KΩ
R2	1KΩ
R	10KΩ
C	1nF

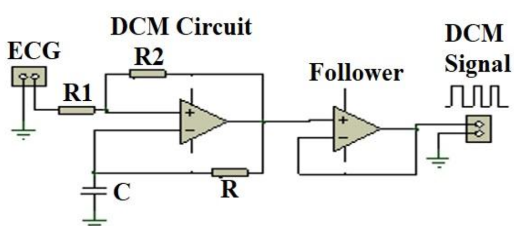


Fig 4. Transmitter module

2.4 Transmission medium

The duty-cycle modulator has already been studied theoretically on a lossless transmission line [24]. Thus, as a continuation of this work, we have opted for a transmission medium offering low attenuation in low frequency and easy access. Hence the choice of the coaxial cable. It can be modeled according to the Telegrapher's equations as a transmission line with loss.

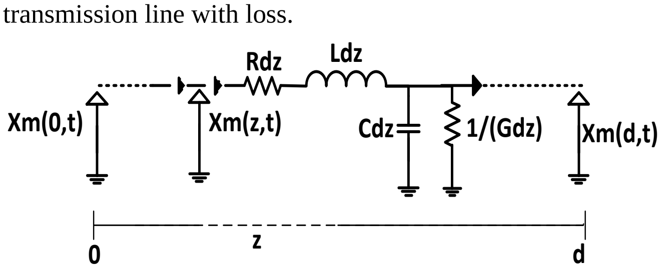


Fig 5. Transmission line with loss

Thus, the signal $x_m(z,t)$ during propagation on line is expressed as follows [25]:

$$\begin{aligned} \frac{\partial x_m(z,t)}{\partial z} &= -Ri_m(z,t) - L\frac{\partial i_m(z,t)}{\partial t} \\ \frac{\partial i_m(z,t)}{\partial z} &= -Gx_m(z,t) - C\frac{\partial x_m(z,t)}{\partial t} \end{aligned} \quad (7)$$

$$\frac{\partial^2 x_m(z,t)}{\partial z^2} = LC\frac{\partial^2 x_m(z,t)}{\partial t^2} + (LG+RC)\frac{\partial x_m(z,t)}{\partial t} + RGx_m(z,t) \quad (8)$$

Where d is the length of the line, R is the resistance, L is the inductance per unit length, C is the capacitance and G is the conductance per unit length. Thus, 1-bit of the modulated signal will have the values $x_m(0,t)$ and $x_m(d,t)$ at the input and output of our transmission line, respectively. For this experiment, we used a 12 m coaxial cable.

2.5 Receiver

Just like the transmitter unit, the receiver is supplied with +5V and -5V. Referring to the work on duty cycle modulation transmission [19], [26-27], it is possible to restore the original signal by appropriately dimensioning a low-pass filter. Since most of the spectral power density of the ECG signal is between 2 and 40 Hz [28], we have sized a second order low-pass filter whose transfer function is described by equations (9) (10) and (11) with a cut-off frequency f_c of about 47 Hz and a static gain Kf=10.49.

$$f(s) = \frac{K_f}{R_3R_4C_2C_3s^2 + \left(R_3C_2 + R_4C_2 + (1-K_f)R_3C_3\right)s + 1} \quad (9)$$

$$f(s) = \frac{\omega_n^2 K_f}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (10)$$

With $\xi = 1.5726$ the damping coefficient of the filter and ω_n the natural pulsation expressed in rad/s.

$$\omega_n = \frac{2\pi f_c}{\sqrt{1 - 2\xi^2 + \sqrt{4\xi^4 - 4\xi^2 + 2}}} \quad (11)$$

The implemented arrangement is shown in Fig. 6 and consists of a shaping circuit to reconstruct the amplitude of the modulated signal in case of attenuation or distortion during transmission and a low-pass filter.

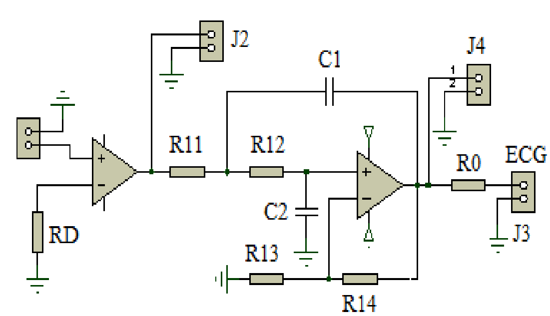


Fig 6. Receiver Circuit Diagram (Low Pass Filter)

The values of the low-pass filter components presented in

Table 2 were obtained by identifying parameters between equations (9) and (10).

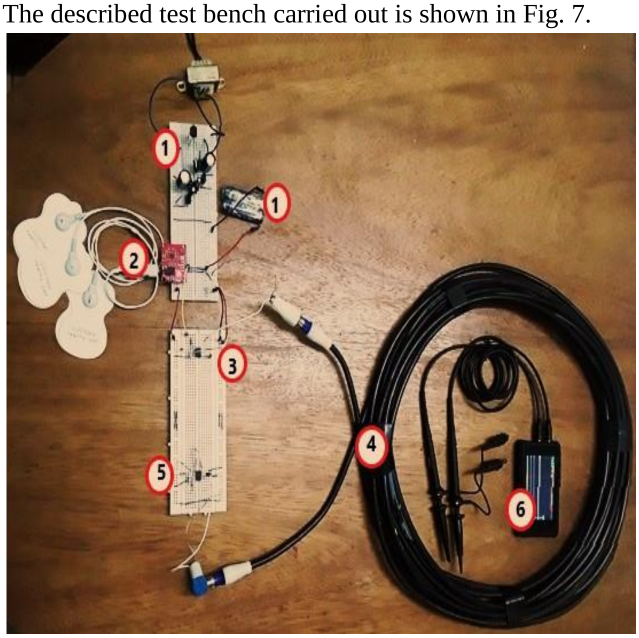
Table 2. Components with receiver values

Components	Values
AOP	TL082
R11	39KΩ
R12	470KΩ
R13	680KΩ
R14	1MΩ
R0	100KΩ
RD	1KΩ
C1	10nF
C2	10nF

3. Results et discussions

3.1 The test bench

The described test bench carried out is shown in Fig. 7.



1 *(Symmetrical power supply ±5V and 2 batteries of 1.5V for power supply of the acquisition system),* ***2*** *(AD8232 ECG signal acquisition kit with electrodes),* ***3*** *(Transmitter by duty cycle modulation),* ***4*** *(Coaxial cable),* ***5*** *(Receiver),* ***6*** *(DS213 oscilloscope).*

Fig 7. Testing workbench

3.2 Temporal analysis

Fig. 8 shows the evolution of the ECG (modulating signal in light blue) in relation to the duty cycle modulated signal (in yellow). There is a total difference in shape, amplitude and frequency between the two signals. This first result illustrates the real time effectiveness of the ON/OFF transformation of the DCM.

Fig 8:. Evolution of the modulated signal (ECG) and the modulated signal

Fig. 9 shows the comparative result of graphs associated with of transmitted and received RMC signals. It can be seen that the characteristics (amplitude, frequency, duty cycle) of the RMC signal are perfectly reconstructed at the end point of the coaxial transmission cable. This makes it possible to envisage a good reconstruction of the ECG modulating signal.

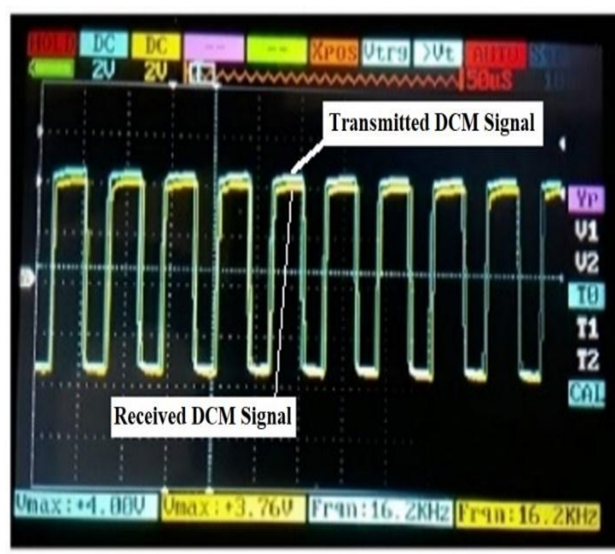


Fig 9. DCM signals transmitted and received (Superposition)

Fig. 10 shows the graphs of the transmitted and received ECG signals, as well as the shape of the transmission error. The curve of the error between the transmitted and reconstructed ECG signals shows:

- A very small error between the two signals
- A delay characterized by the presence of peaks corresponding to P, Q, R, S and T waves.

a)
b)

***a** (Transmitted and received ECG signal), **b** (Error graph)*

Fig 10. Transmitted and reconstructed ECG signals (after attenuating resistor) + transmission error

It is important to note that the slight delay in the appearance of the peaks of the waves (P, Q, R, S and T) transmitted and reconstructed is due to the signal transmission time on the coaxial cable and the response time of the DCM transmitter and the active demodulator filter. Fortunately, this delay is invariant in time, in which case the time intervals between the appearance of the peaks of the said P, Q, R, S and T waves do not change.

4. Conclusion

This paper is the first experimental confirmation of the feasibility and quality of DCM transmission systems for ECG signals on a wired propagation medium. The real-time test results presented and commented, were obtained on a structurally simple experimental prototype that can be easily realized without special components. This is therefore a new effective, technically and technologically oriented approach to the implementation of remote medical instruments. Nevertheless, in order to achieve this, it would be necessary to experimentally determine the standardized characteristics of the transmission such as: SNR, THD, SINAD, SFDR, NFR, etc. It would also be exciting, in the framework of more ambitious research projects, to substitute and test in practice the coaxial cable transmission medium used in this paper, by a fiber optic transmission channel. This more ambitious medical remote instrument, under studied, may lead to a patentable product.

Conflict of Interest

The authors declare that they have no conflict of interest

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