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A novel FPGA-Based Multi-Channel Signal Acquisition System Using Parallel Duty-Cycle Modulation and Application to Biologic Signals: Design and Simulation

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***Abstract* – This paper presents the design and simulation of a new FPGA-based multichannel signal acquisition system, involving parallel DCM (duty-cycle modulation) of four biologic signals, i.e., respiratory, PPG (photoplethysmography), ECG (electrocardiography) II and V. Then, the resulting modulated inputs are simultaneously oversampled and converted into digital waves, by a low-pass decimation IIR (infinite impulse response) filter per channel. The relevant novelty brought by this new multichannel signal acquisition scheme, relies on a number of merits, e.g., 01 basic DCM circuit and 01input pin (or bit) of the FPGA per analog channel, IIR filter with 30 Hz cut-off frequency per channel (then no need of 50 or 60 Hz notch filters). As relevant merits, the proposed multichannel architecture offers minimum interfacing hardware while requiring minimum software resources. The virtual model of that acquisition system, is designed and implemented in Matlab/Simulink framework, using: a) modulating biologic signals (imported from Physionet bank); b) *Simulink blocks* for DCM interface and *DSP Builder blocks* (for parallel IIR filters); c) 50 MHz sampling frequency, with 60 bits precision coefficients; and d) virtual oscilloscopes. The predicted results presented for 04 biologic signals, are very satisfactory. In future research works, the VHDL code will be generated and compiled in Quartus II for uploading into DE10-NANO-SoCFPGA, in order to build our new FPGA-based multichannel biomedical instrument.**

Keywords-Multichannel, signal acquisition, duty-cycle modulation, biologic signals, DSP-Builder, FPGA

I. INTRODUCTION

Acquisition of biologic signals such as the electrocardiograph (ECG) for digital processing usually requires the use of a conventional ADC, with a transducer module consisting of filters and amplifiers. However, the high performance of oversampling converters allows acquisition with hardware reduction of the analog part. The sigma-delta converter is generally used for this purpose [1, 2, 3].

Despite the great performance of the sigma-delta converters, its hardware and software structure still remain a very big challenge because they require a complex circuit consisting of switched capacitors and a great number, digital decimator filters and CIC filter (if any) consuming significant amount of memory and computational resources [4, 5]. To overcome these drawbacks, a new ADC topology with better performance has been developed and tested in [6]. It is known as DCM-based ADC (analog-to-digital conversion), and has proved to become a versatile emerging signal processing technique, in industrial and communication electronics.

The DCM technique is actually used as a modern oversampling ADC technique. It facilitates the digital acquisition of “n” analog signals via a single n-bit port of a microcontroller. The digital reconstruction of modulating signals in such a DCM-ADC is usually done by a simple RII low pass filter. The first DCM-based analog-to-digital converters were initiated in a single-channel context in [6], then in a multi-channel context in [7], with an implementation on a desktop PC compatible hardware running a software developed with Microsoft Visual Basic 6.0 for standard signals such as: sinusoidal, square and triangular. On the one hand, the use of the PC as a hardware target here has resulted in limits in the performance of the ADC (Bandwidth, real-time operation). Moreover, the parameters used for the modulator were not optimized since the objective aimed here was to validate the DCM-based ADC principle.

Although the modulating band offered was very limited due to the frequency limits of the PC LPT ports, later, the microcontroller technology proved more merits in [8], followed in [9] and [10] by FPGA technology with the best qualities and performances. The particularity of this article is to exploit the simplicity of the electronic structure of the MRC modulator, to carry out the acquisition of biological signals in a multichannel situation. On the other hand, the insensitive nature of the MRC modulator to noise and the use of the permanent FPGA to digitally achieve certain high-pass filters which would have been produced analogically in the case of

conventional ADCs, are an asset to the proposed solution. The advantages offered by DCM technique in the *multichannel* ADC contexts are: a) reduction of hardware complexity; b) use of a single digital low pass demodulation filter per channel for the construction of the signals; c) no need for Notch filter as in [1, 2]. To improve the precision of a DCM based ADC, an optimization technique has been developed and tested in [11].

Except the analytical basis initiated in the pioneering paper [7], there is a great lack of multichannel DCM-based ADC systems in the electronics literature. Thus, this article aims to design and simulate a first virtual prototype of a FPGA-based multichannel acquisition system, for many biologic signals.

In the remainder of this article, the fundamentals of DCM-based multichannel ADC will be recalled in section II from scientific basis available in **[7]**. Then, section III will outline the methodology and research tools used, followed in section IV by the simulation results obtained. Finally, the paper will be concluded in Section V.

II. RECALL ON MULTICHANNEL DCM-ADC FUNDAMENTALS

The waveform of a typical DCM signal in channel j (j=1, 2, 3, 4), without lost of generality, is presented in Fig. 1.

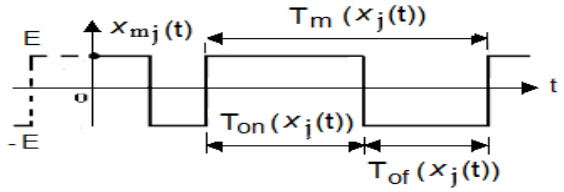

Figure 1. Waveform of DCM Signal in channel j

According to fig. 1, a DCM waveform is a switching a periodic wave $x_m(t)$ given as follows [7]:

$$x_{mj}(t) = \underbrace{\left(2R_m(xj(t)) - 1\right)E}_{\text{Low Frequency Terms}} + \underbrace{\sum_{n=1}^{\infty}\left(\left(\frac{4E}{\pi}\right)\frac{\sin\left(n\pi R_m(xj(t))\right)}{n}\cos\left(2\pi n\frac{t}{T_{osc}(xj(t))}\right)\right)}_{\text{High Frequency terms}} \quad (1)$$

where, $R_{mj}(x(k)) = \dfrac{T_{ON}(x_j(k))}{T_m(x_j(k))}$ is given by (2)

$$R_{mj}(x(k)) = \frac{T_{ON}(x_j(k))}{T_m(x_j(k))} = \frac{\ln\left(\dfrac{\alpha_{2j}x_j(k) - (1+\alpha_{1j})E}{\alpha_{2j}x_j(k) + (\alpha_{1j}-1)E}\right)}{\ln\left(\dfrac{\left(\alpha_{2j}x_j(k)\right)^2 - \left((1+\alpha_{1j})E\right)^2}{\left(\alpha_{2j}x_j(k)\right)^2 - \left((\alpha_{1j}-1)E\right)^2}\right)} \quad (2)$$

And α1j and α2j = 1- α1j being constants channel j. It has been shown that an excellent linear approximation of in a wide neighborhood of [0, ½] is given by (3) as follows [7]:

$$R_m(x_j(t)) = \beta_j\, x_j(t) + \frac{1}{2} \text{ with } \beta_j = \frac{\dfrac{\alpha_{1j}\alpha_{2j}}{E(1-\alpha_{1j}^2)}}{\log\left(\dfrac{1+\alpha_{1j}}{1-\alpha_{1j}}\right)} \quad (3)$$

From the digital signal processing side, it has been also proved in [7] that, a second order low pass IIR filter, can be used downstream the sampled DCM signal, to extract the modulating x(t). Moreover, its transfer function is:

$$F_{cj}(s) = \frac{K_{fj}w_{nj}^2}{s^2 + 2\zeta_j\, w_n j\, s + w_{nj}^2} \quad \text{where } K_{fj} = \frac{1}{2\beta_j E} \quad (4)$$

In a DCM-based ADC, each transfer function of filter j (j =1, 2, 3, 4), has to be discretized using Tustin method in order to obtain its discrete recurrence equation to be implemented and stored in the target DSP (digital signal processor), which is a DE10-NANO-SoC FPGA. At the end of this recall section, it is worth noting that the discrete recurrence equation of the IIR associated with each j channel, is given as follows [7]:

$$\begin{cases} yj(0) = a0\ \ xj(0) \\ yj(1) = a0\ xj(1) + a1\ xj(0) - b1\ yj(0) \\ yj(k) = a0\ xj(k) + a1\ xj(k-1) + a2\ xj(k-2) \\ \qquad - b1\ yj(k-1) - b2\, yj(k-2) \end{cases} \quad (5)$$

with j =1, 2, 3, 4 (four biologic signals).

III. METHODOLOGY AND RESEARCH TOOLS

The new multichannel biologic signal acquisition system is described by the block diagram presented in Fig. 2, and the corresponding Matlab/Simulink model is shown in Fig. 3.

In the proposed system, the sensors of biologic signals, involve very low frequencies. Each signal is then pre-amplified according to the characteristics of the sensors used. Then, a high-pass filter is used because biologic signals are generally affected by very low frequency noise due to Respiration, movement, poor contact of the electrodes on the skin. The related noise frequency is estimated up to 0.1 Hz (in the case of ECG) and 0.5 Hz (in the case of PPG). Thus the cut-off frequencies will be respectively in the same proportion. The set of p-signals are then sent to p = 4 parallel DCM inputs according to the number of signals.

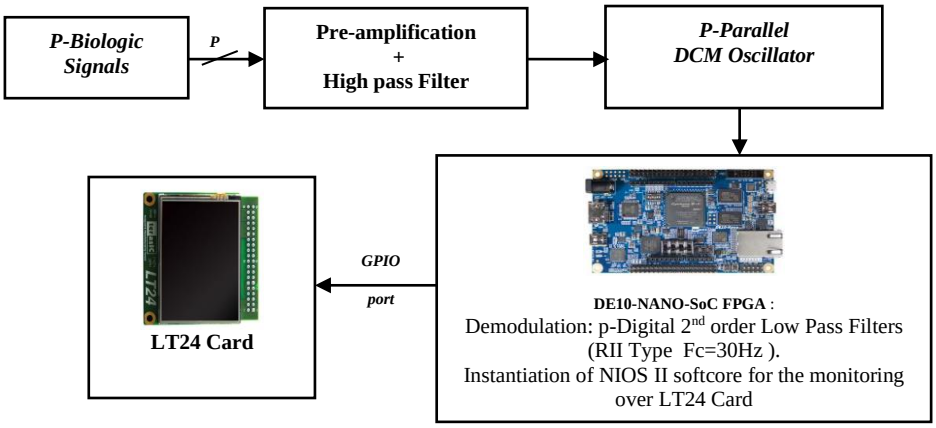

Figure 2. Block diagram of FGGA-based multichannel acquisition system for biologic signals

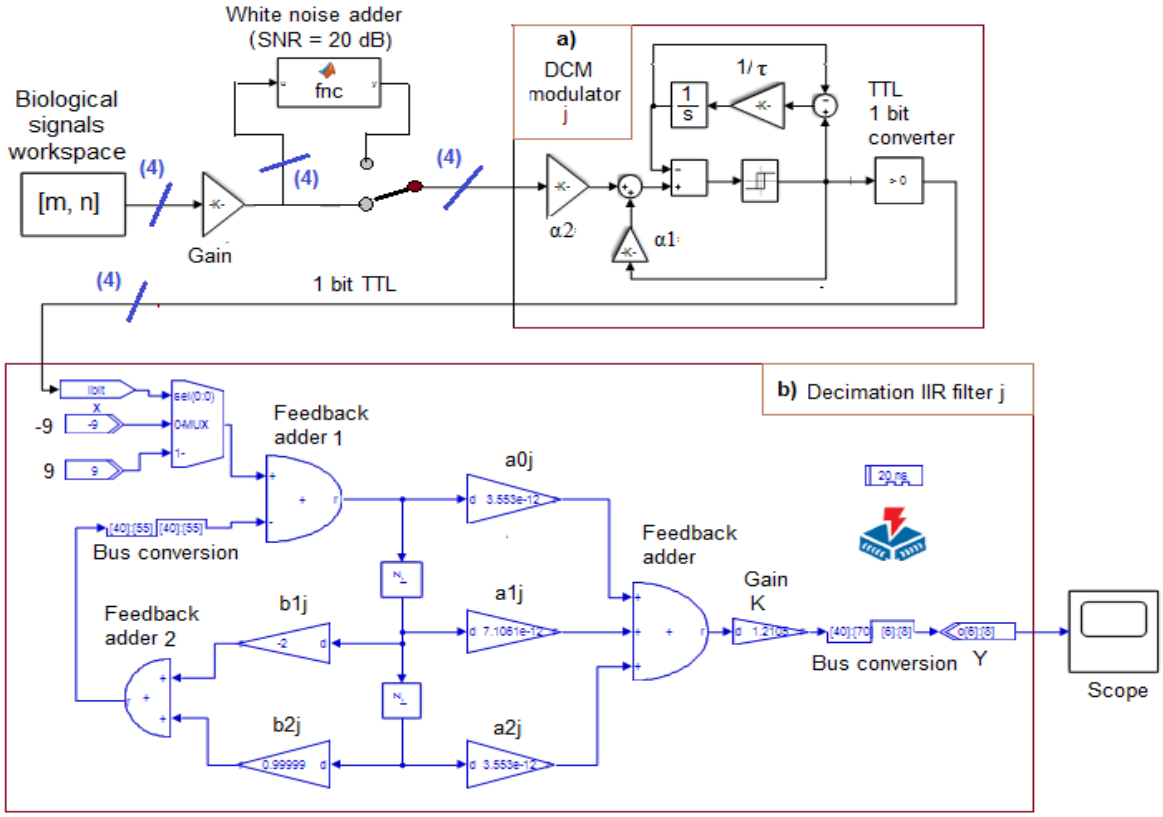

Figure 3. Matlab/Simulink virtual model of p = 4 channels acquisition system for biologic using parallel DCM

The DCM modulators use optimum parameters to modulate pre-amplified signals in a frequency range, from 1 KHz to 5 KHz. Each modulator delivers a 1-bit stream signal to a FPGA pin. The reconstitution of *p* modulating signals is done by means of simple digital low-pass second order filter (each per channel j), which were designed in Matlab/Simulink environment according to (5), using DSP-Builder toolbox, with appropriate cutoff frequency fcj = 30Hz for each j channel. Indeed, the bandwidth of the respiration signal is up to 4 Hz [12], that of the PPG is in the order of 0.05 to 20 Hz according to [13], and the case of ECGs being 0.05 to 100 Hz for the standard 12-leads clinical Kind, with 0.5-50Hz for critical conditions (such as intensive care or ambulance patients), and around 17 Hz for the measurement for rate Kind [14]. Even though the bandwidth of the ECGs is greater than the cutoff frequency of our system, it should be noted that the major part of the spectral power of the ECG is between 2Hz-40Hz. Then, a 0.5-30Hz band pass filter could be used to filter its embedded noise [15]**.** As an example, for the ECG channel where fcj = 30 Hz, with sampling frequency fs = 50 MHz. In which case, a choice of a 50 Hz or 60 Hz Notch filter [1, 2], is useless for a cutoff frequency of the related IIR filter. At this research step, the next works deal with the *implementation* and *well testing* of the virtual model of the whole FPGA-based multichannel signal acquisition system shown in Figure 3, using Matlab/Simulink and DSP builder blocks. Followed by VHDL description code generation, and compiling under Quartus II. Finally, the NIOS II system with various peripherals could be synthesized and connected to the DCM demodulation module and to a

LT24-LCD screen module, for a better monitoring of biologic signals. However, this paper only presents a virtual prototyping of that new multichannel biomedical, and very satisfactory and promising simulation results, obtained for 04 types of real biologic signals imported into Matlab/Simulink from Physionet Bank [16].

IV. VIRTUAL SIMULATION RESULTS AND DISCUSSIONS

A. Virtual simulation results

The relevant simulation tools are listed as follows:

- Matlab/Simulink R2017b;
- DSPbuilder 18.1.0.625
- Quartus II Prime 18.1 standard edition;
- PC core i7 computer, 500G and 4G of RAM;
- Physionet signals Bank, as a source of 03 types of target biological signals. A preliminary analysis and comparison of their power spectral diagrams, has shown that the involved maximum bandwidth is 40 Hz.

The parameters properties used for each block in figure 3 are:

- For the Physionet.org ID
  Database bidmc01m [17] with 04 signals used, shown in Fig. 4 and attenuation gain per channel is

```
Source: record bidmc/bidmc01
val has 5 rows (signals) and 1250 columns (samples/signal)
Duration:     0:10
Sampling frequency: 125 Hz  Sampling interval: 0.008 sec
Row Signal  Gain    Base    Units
1   RESP,   65534   -32767  pm
2   PLETH,  138229.4494 -63710  NU
3   V,  32670.9091  -16367  mV
4   AVR,    42414.137   -11643  mV
5   II,     32670.9091  -16367  mV

To convert from raw units to the physical units shown
above, call the 'rdmat.m' function from the wfdb-matlab
toolbox: https://physionet.org/physiotools/matlab/wfdb-app-matlab/
```

Figure 4. Bidmc01 source from Physionet.org ID Database [17]

1/40000 and noise for SNR = 20 dB using Matlab *awgn* function.

- For 4 DCM Oscillators
  $\alpha 1j = 0.195006372593921$; $\alpha 2j = 1-\alpha 1j$; $\tau j = 0.000253118139616$; E=9V; F_{maxj}= 5 KHz and F_{minj}=1KHz;
- For digital IR filters, generated using Matlab *fdaTool*:
  a0j=3.553e-12; a1j=7.1061e-12; a2j = 3.553e-12; b1j= -1.9999; b2j= 0.9999; Kj= 1.210; Fcj =30Hz and f_{sj}=50 MHz.

It should be noted that at the time of the filter implementation, we are using fixed point encoding in DSP-Builder. Since the coefficients of the filter are very small values, the use of 60 coding bits here makes it possible to achieve the required precision of the coefficients which guarantees the stability of the filter.

Beside to a visual comparison from the plots of modeling and related demodulated signal in each case printed in fig. 6 and fig. 7, we resorted to the standard RMSE (root mean square error) criterion, computing in each case from numerical simulation data, as given by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x-x)^2}{n}} \qquad (6)$$

where *n* stands for the size of the discrete time sample, being pure modulated and corresponding modulated signals. The results obtained when computing (6) for all cases are summarized in Table II.

Other important dynamic parameters of the DCM-based ADC designed here are summarized in Table I. In fact, we have used *snr, sinad and thd* Matlab function to compute signal to noise ratio (SNR), signal to noise and distorsion ratio (SINAD) and Total Harmonic Distortion (THD) in Matlab with sinusoidal full-scale test 2Hz frequency. Then ENOB is deduced by (7):

$$ENOB = \frac{SINAD - 1.76}{6.02} \qquad (7)$$

TABLE I. DYNAMIC PARAMETERS OF THE DCM-BASED ADC

Parameters	Values
SNR	69.5004 dB
SINAD	64.0473 dB
THD	-1.4528
ENOB	10.34 = 11 bits

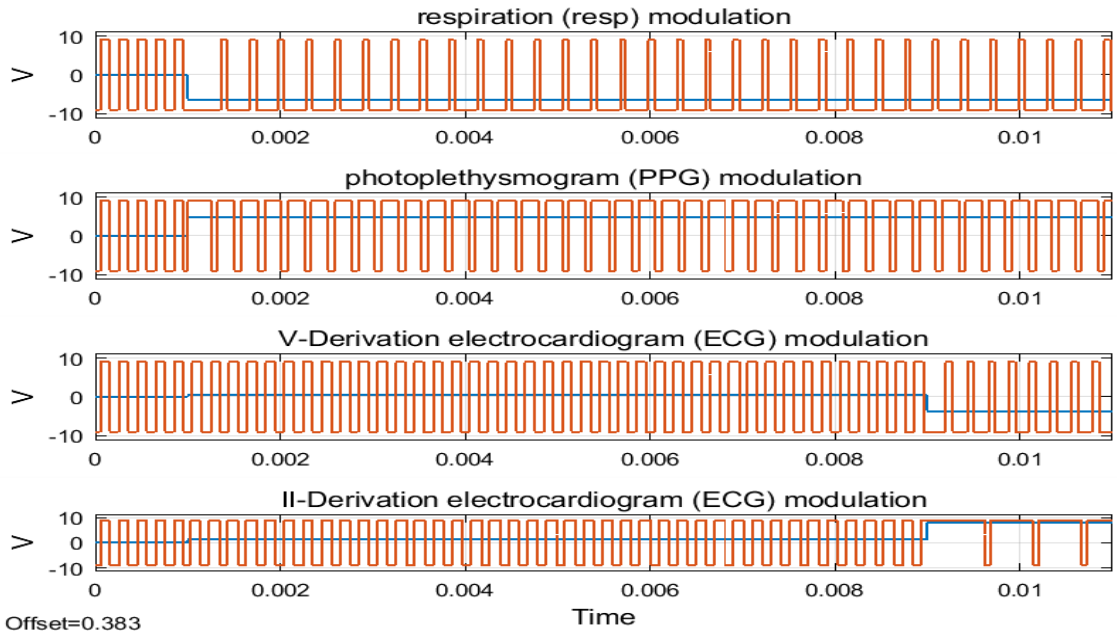

Figure 5. DCM signals

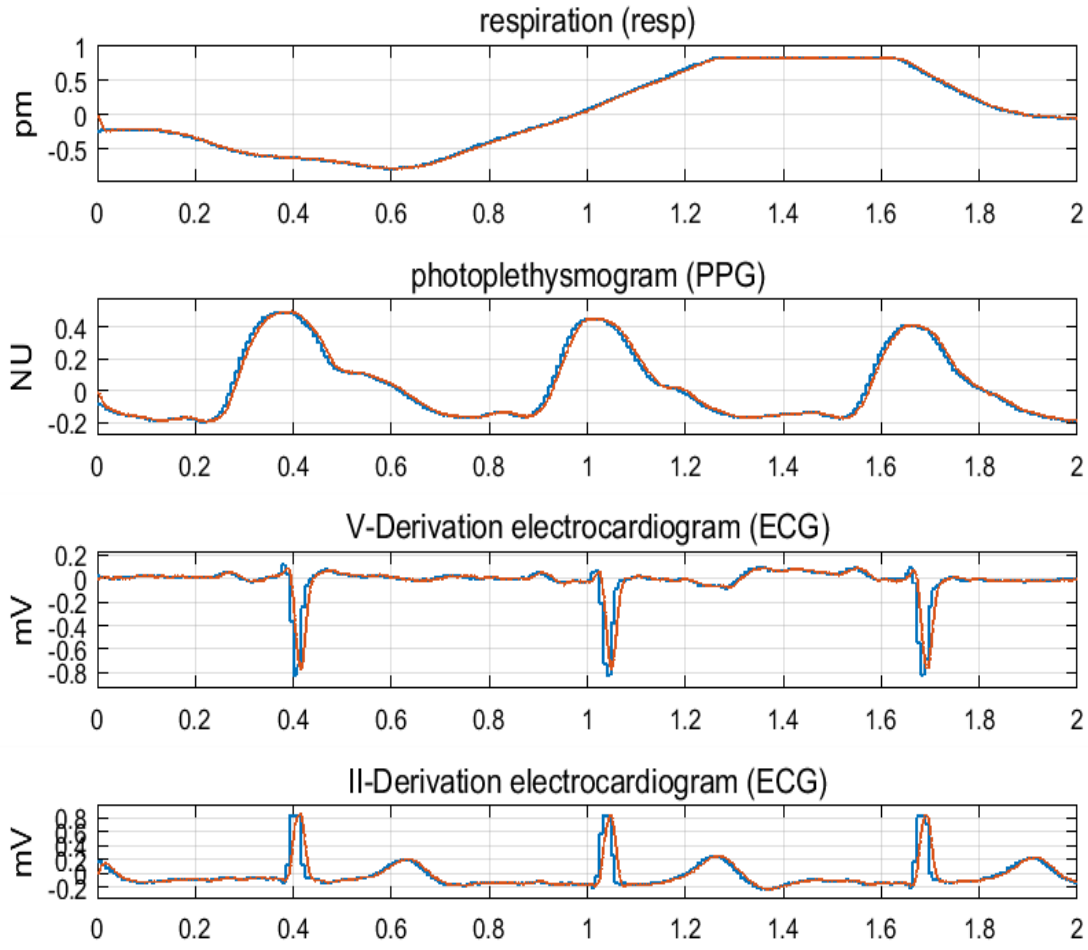

Figure 6. Comparison of modulating biologic signals (in blue) and their corresponding demodulated wave (in red)

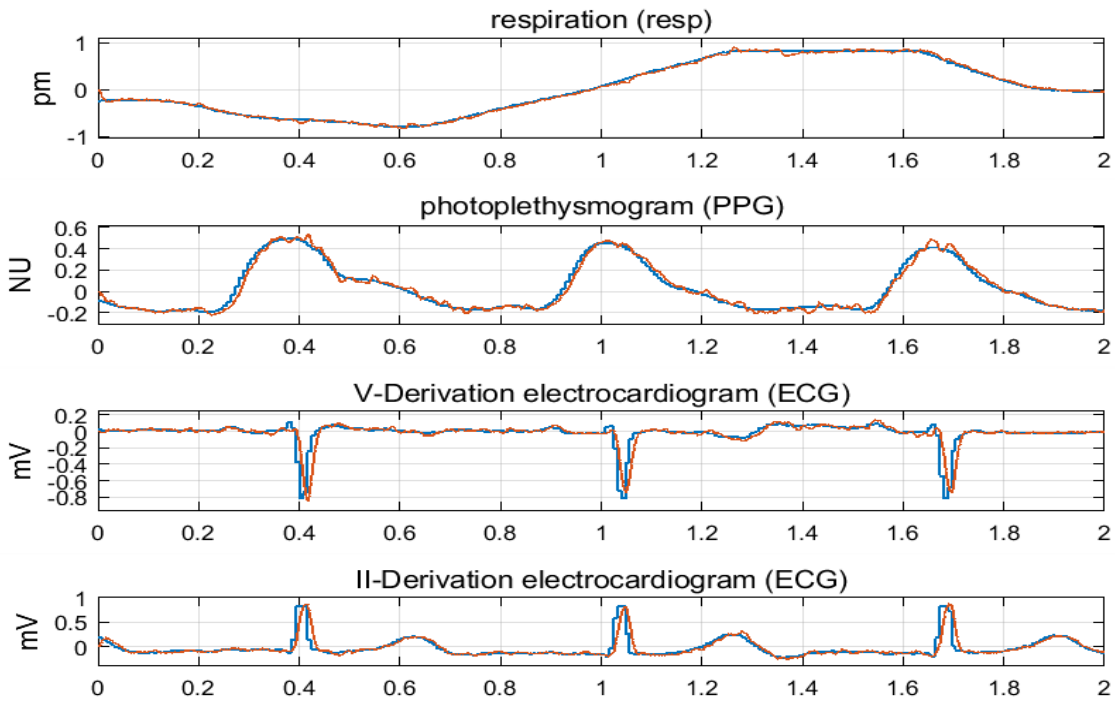

Figure 7. Comparison modulating biologic signals (in blue), and their corresponding noisy demodulated wave for SNR =20 dB (in red)

TABLE II. RMSE OF THE DCM PROCESS (NOISYLESS CONDITIONS)

Noiseless biologic signals		**Noisy biologic signals** (for SNR = 20 dB)	
Signals	**RMSE**	**Signals**	**RMSE**
RESP	0.003594	RESP	0.1759
PPG	0.009934	PPG	0.2226
ECG-V	0.04314	ECG-V	0.2227
ECG-II	0.05084	ECG-II	0.4758

B. Discussion of the results

Fig. 5 makes it possible to confirm, as in [6], that the duty-cycle modulator frequency evolves according to the modulating signal profile.

In fig. 6, we can see the reliable reconstruction of all modulating biological signals involved (in red), under noiseless conditions. It is worth noting in fig. 7 that, similar findings also hold under noisy conditions.

In Table II, the RMSE computed under noiseless conditions reflects a very high *intrinsic* quality of the DCM process. This is a challenge due to numerous merits of DCM strategy as reported in the literature. Even under a high additive input high noise, it is a challenge also that the combined RMSE remains low. This comparative study is relevant, since according to [1, 2, 15], the acquisition of the ECG signal, up to date, involve high pass filter, low pass filter, Notch cut filter, and even wavelet transform methods requiring greedy resources for calculus [18].

Moreover, the DCM-based ADC developed in this paper present better performance compared to the commercial ADC used for ECG, e.g., ADS1298. Indeed, even though the ADS128'IC has 24-bits ADC, it embeds Delta-sigma ADC which uses a 2^{nd} order modulator [19,20]. This structure is very complex compared to that of the DCM hardware which consisting of just 03 resistors, 01 capacitor and 01 operational amplifier. In addition, the digital decimation filter on each channel of ADS128 consists of a third-order sinc filter requiring complex calculus for 24-bit resolution, while the technology developed consists of a 2^{nd} order demodulation filter for 12-bits. Finally, the DCM-based ADC technology used needs only a simple terminal wave receiver, for both demodulation and noise filtering operations. Table III shows relevant comparative data of ADS1298 and DCM-based ADC.

TABLE III. COMPARISON OF ADS1298 AND DCM-ADC

	ADS1298	**DCM-ADC**
Resolution	24 bits	12 bits
Hardware structure	Complex : 3^{rd} order $\Delta\Sigma$	Simple
Demodulation filter	3^{rd} order sinc	2^{nd} order IIR
Denoise filter	Analog and digital	Demodulation digital filter

CONCLUSION

The mayor scientific contribution of this paper has been, to extend the theoretical and virtual knowledge base, existing up to date on single-channel DCM-

Based ADC technology, to FPGA-based multichannel ADC systems. Many samples of modulating biologic signals (ECG, PPG, respiration), have been used here to test the relevant characteristics of the proposed multichannel ADC technology. The simulation framework and results have confirmed its minimal hardware and software architecture, while offering great performance levels. The continuation of this work in future research opportunities, will be to synthetize at the hardware level, a real prototyping FPGA-based multichannel ADC system, in order to prove its effective reliability for real time applications.

CONTRIBUTION OF AUTHORS

OTAM Steve Ulriche, *Ph.D. student*, is the main author of the paper. He contributed to relevant improvements of the research work conducted in his Master II Thesis, with relevant application to simultaneous modulating biologic signals. He carefully implemented revisions requested by his co-authors. Moreover, he contributed also to the preparation and edition of the manuscript of this paper according to JEEECCS Template.

MOFFO LONLA Bertrand, *Senior Lecturer*, contributed to the design and synthesis of the digital demodulator filter at the level of the FPGA fabric. He provided a great assistance for the search of solution to the shortcomings raised by the main supervisor of this research work. He also helped edit and translate the final version of the article into English.

GAMOM NGOUNOU E. R. Christian, *Senior Lecturer*, contributed to proofreading the different parts of the article and to remove typing errors, to improve translation of some sentences. He also made valuable suggestions for the choice of a few relevant parameters of the designed system.

MBIHI Jean, *Full Professor*, is the corresponding author of the paper. He provided relevant guidelines for the research methodology, adopted in this paper. He contributed to the organization and supervision of the works presented in this paper, as well as to the copyright ethic verification of its whole content. He requested to the main author to clarify the choice of identical sampling period and IIR filters for channels with different types of modulating biologic signals. He requested also to the main author, to outline a more relevant evaluation criteria of DCM performance, using related RMSE values as reported in Table II. He also checked and validated corrections and significant improvements, conducted in the final revised paper by other co-authors, as requested by JEEECCS reviewers.

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