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Experimental Assessment of a Novel CS-based Acquisition Method for ECG Signals in IoMT

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***Abstract* – The paper presents the results obtained from a preliminary experimental assessment of a novel method which relies on Compressed Sampling (CS) of electrocardiographic (ECG) signal. The mathematical model for CS-based acquisition of ECG signals and its feasibility for practical implementation for an Internet-of-Medical Things (IoMT) system are described. Herein, the presented experimental results demonstrate the robustness and convenience of the proposed method.**

***Keywords* – Internet of Things, Sampling, Compressed Sensing, ECG Signal, Embedded Systems.**

I. INTRODUCTION

Internet of Things (IoT) represents a new paradigm for *machine*-to-*machine* communication, where the *things* are augmented with smart sensors and Internet connectivity in order to observe various physical quantities, collect information, transmit, store and analyse the acquired data [1]. Biomedical smart sensors adopting IoT paradigm (i.e. thus forming instrumentation for patient monitoring), represent the Internet-of-Medical-Things (IoMT) for connected health.

Patient mobility requires that many of such biomedical smart sensors (i.e. forming wearable instrumentation) are battery powered. For instance, signals like the electrocardiogram (ECG) are used for identification of arrhythmia or irregular abnormalities. This process of patient monitoring requires long-term ECG records. Consequently, connected health wearable instrumentation is strongly dependent on the energy cost for wireless transmission [2]. Therefore, the energy consumption will define the practicability of wearable instrumentation in case of long-term recording of bio-electrical signals [1]-[3]. For this reason, the research direction is motivated on developing wearable devices which embeds smart sensors and exhibits low power consumption.

The research activity presented in this paper is part of the project titled Ambient-intelligent Tele-monitoring and Telemetry for Incepting & Catering over hUman Sustainability, ATTICUS, supported by the Italian Ministry of Education and Research, which aims to develop a smart wearable device for the monitoring of several vital parameters by adopting novel technologies for minimizing the power consumption [4].

The general architecture of the ATTICUS system consists of: (i) a smart wearable device (S-WEAR), (ii) an ambient intelligence device (S-BOX), (iii) a Decision Support System (DSS), and (iv) a monitoring station.

The S-WEAR is composed by a T-shirt (i.e. worn by the user) enriched with smart sensors providing: (i) from one up to twelve leads ECG measurements, (ii) user activities information (i.e. step counting, fall detection, orientation, position), (iii) skin temperature, (iv) bio-impedance measurements for estimating the galvanic skin response, (v) respiration rate, and (vi) heart rate measurements. All those measurements have to be stored on a local SD card and sent to the S-BOX via low-energy wireless communication (e.g. Bluetooth Low-Energy, BLE, interface). In order to reduce the amount of data transmitted to the S-BOX, data compression algorithms have to be implemented on the S-WEAR.

Continuous monitoring of bio-electrical signals (e.g. ECG, electroencephalography (EEG), heart and respiration rates, blood pressure, etc.) requires designing robust sensing schemes, for the signals information acquisition, in order to allow data reduction (i.e. prior to the transmission) at the smart sensor level. For that reason, sparse behaviour of bio-electrical signals has led to research and development of Compressed Sensing (CS) signal processing frameworks. Accordingly, CS-based sampling schemes have become popular and in literature [5]-[7]. Furthermore, developments of IoT prototypes for ECG signal monitoring [8-9], as well as digital signal processing algorithms for ECG signal quality improvement have been also reported in literature [10-11].

In [12], a novel method for CS-based sampling of ECG signals for IoMT has been proposed. Based on that work, in this paper, an initial experimental assessment of the method is presented. This assessment is necessary in order to validate the method for the S-WEAR design.

The paper is organized as follows. Section II describes the adopted CS-based method. In Section III,

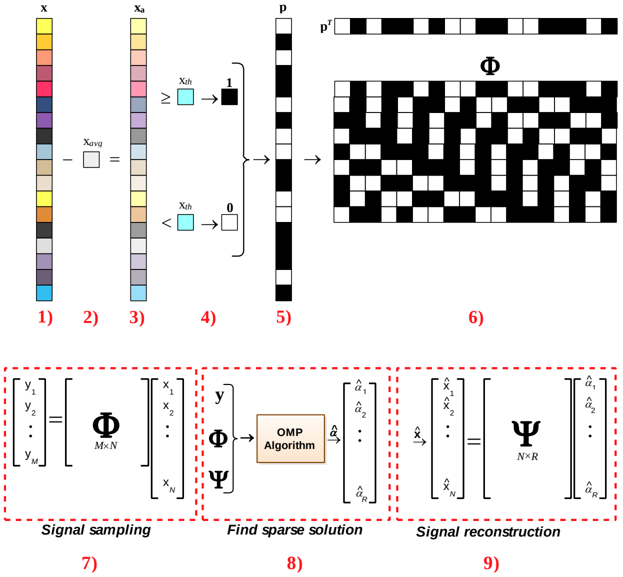

Fig. 1. The processing steps of the adopted novel CS-based sampling method.

the IoT prototype is presented. The experimental setup and the experimental results are described in Section IV. Several conclusions and future work are reported in the last Section of the paper.

II. DESCRIPTION OF THE METHOD

In this Section, the adopted CS-based method for practical ECG compression is shortly described. This approach was firstly presented in [12] and it is based on a sensing matrix which contains information related to the auto-correlation coefficients from the observed signal.

In particular, for one lead ECG signal compression, the method performs the following steps (see Fig.1):

Step 1. Acquisition of a vector **x** of *N* samples containing at least one period of the ECG signal.

$$\mathbf{x} = [x_1, x_2, x_3, \dots, x_N]^T \tag{1}$$

Step 2. Based on this vector, the average value, $\mathrm{x}_{\mathrm{avg}}$, is calculated.

$$\mathrm{x}_{\mathrm{avg}} = \frac{\sum_1^N x_i}{N} \tag{2}$$

Step 3. The absolute value of the point-by-point difference between the **x** vector and its average value, $\mathrm{x}_{\mathrm{avg}}$, is performed, thus obtaining the vector $\mathbf{x_a}$:

$$\mathbf{x_a} = \left|\mathbf{x} - \mathrm{x}_{\mathrm{avg}}\right| \tag{3}$$

Step 4. The vector $\mathbf{x_a}$ is compared point-by-point with a threshold value, x_{th}.

Step 5. The vector **p**, $N \times 1$, is built as follow: (i) if the element of $\mathbf{x_a}$ is higher than the x_{th}, the value 1 is inserted in the corresponding vector position of **p**, (ii) if the element of $\mathbf{x_a}$ is higher than the x_{th}, the value 0 is inserted in the corresponding vector position of **p**.

Step 6. Each row of the sensing matrix **Φ** is obtained by circular shifting of the vector $\mathbf{p}^{\mathrm{T}}$. The number of shifted samples is equal to the desired compression ratio, *CR* = *N*/*M*, where *M* is the number of compressed samples and it corresponds to the number of the **Φ** rows:

$$\mathbf{\Phi} = \begin{bmatrix} \mathrm{p}(1) & \mathrm{p}(2) & \cdots & \mathrm{p}(\mathrm{N}) \\ \mathrm{p}(\mathrm{N}-\mathrm{CR}+1) & \mathrm{p}(\mathrm{N}-\mathrm{CR}+1) & \cdots & \mathrm{p}(\mathrm{N}-\mathrm{CR}) \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{p}(\mathrm{CR}+1) & \mathrm{p}(\mathrm{CR}+2) & \cdots & \mathrm{p}(\mathrm{N}) \end{bmatrix} \tag{4}$$

Step 7. The *M* compressed samples, which are contained in vector **y**, are obtained from the multiplication between the sensing matrix **Φ** and the vector **x**:

$$\mathbf{y} = \mathbf{\Phi x} \tag{5}$$

Step 8. At the receiving side, the *R* coefficients $\hat{\boldsymbol{\alpha}}$ in the domain defined by the Mexican Hat wavelet matrix, **Ψ**, (see [12]) are obtained from the compressed vector **y** by knowing the sensing matrix **Φ** and by using the Orthogonal Matching Pursuit (OMP) algorithm.

Step 9. The signal reconstruction process is performed by multiplying the estimated vector $\hat{\boldsymbol{\alpha}}$ with the Mexican Hat wavelet matrix, **Ψ**. From this multiplication, the vector $\hat{\mathbf{x}}$ is obtained (see Fig.1).

III. THE IoT PROTOTYPE

As reported in [4], S-WEAR has to provide at least: (i) sufficient quality of signal measurements related to the monitored bio-parameters, (ii) low energy consumption, (iii) low amount of data stored, and (iv) high compression of data for transmission.

The S-WEAR architecture consists of five modules [4]: (i) the smart T-shirt, which embeds all the electrodes for acquiring the ECG signals, the bio-impedance and two-point skin temperatures, (ii) the core module, (iii) the extended ECG module, (iv) the position measurement module, and (v) the Internet interface module.

In particular, the core module comprises: (i) a microcontroller unit, with a BLE transceiver integrated on-chip, (ii) two skin temperature sensors, (iii) one lead ECG sensor, (iv) one bio-impedance sensor, (v) a respiration rate sensor, (vi) an IMU and 3-axis magnetometer sensor, (vii) an SD card memory card, and (viii) the battery with the associated power distribution network.

According to the previous mentioned architecture of the core module, in this Section, a test microcontroller has been chosen and its features are described below. Furthermore, the developed software which implements the CS-based method described in Section II, is reported.

A. Hardware

As development platform, the Cypress Semiconductor CYW920719Q40EVB-01 evaluation board [13] was chosen for the implementation of the mentioned CS method. This platform contains a CYW20719 System-on-Chip (SoC) based microcontroller, which comprises the BLE 5.0 capabilities.

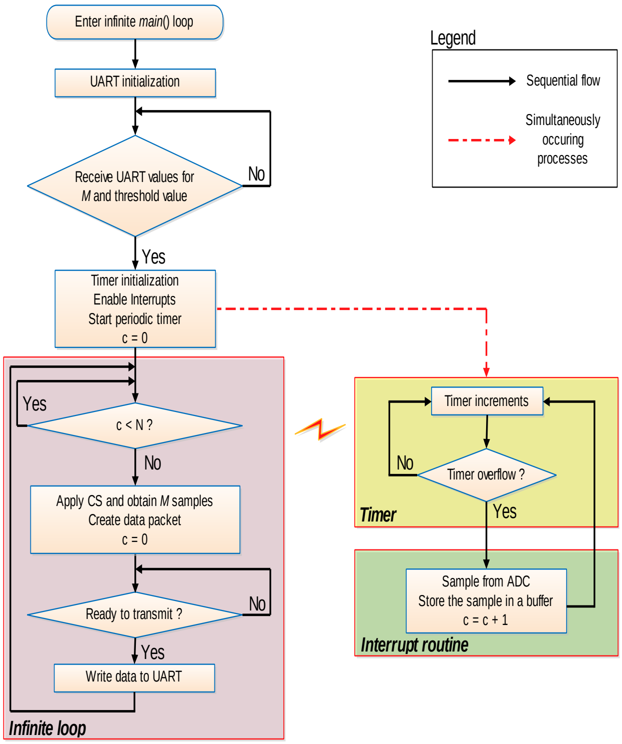

Fig. 2. Flowchart of the developed firmware running on the CYW920719Q40EVB-01 evaluation board.

The CYW20719 is a 96 MHz ARM Cortex M4 type processor with floating-point unit, making this SoC a powerful platform which is optimized for low power consumption applications. The CYW20719 includes: (i) two Serial Peripheral Interface (SPI) interfaces, (ii) two Universal Asynchronous Receiver Transmitter (UART) interfaces, (iii) two Inter-Integrated Circuit (I2C) interfaces, and (iv) 28 channels for the single 13-bit Σ-Δ Analog-to-Digital Converter (ADC).

As first implementation, the ECG signal has been connected directly to the A0 channel of the ADC. The programming, debugging and user interaction with the platform is done by the UART interface.

B. *Software*

The firmware for the CYW20719 SoC was developed in WICED Studio. The aim of the implemented firmware is to acquire, compress and transmit to the PC, the ECG signal.

A synthetic flowchart of the software is presented in Fig. 2. At the beginning, the microcontroller waits for receiving via UART: (i) the *M* value, which corresponds to the number of compressed samples, and (ii) the threshold value x_{th}. Subsequently, a periodic timer of 2 *ms* is started. When the interrupt event related to the timer occurs, the interrupt routine is performed.

During this routine, a sample of the ECG signal from the ADC block is acquired and then stored in a buffer of length *N*. The *N* value is chosen by the user. On the other hand, when the interrupt event is not taking place, the infinite loop routine is performed.

At the beginning of this routine, the number of acquired samples is checked. If this number is equal to *N*, the CS-based method is performed on the buffer, thus obtaining the **y** vector of compressed samples. After that, the obtained **x**, **y** and **p** vectors, are sent to the PC via UART.

IV. RESULTS AND DISCUSSIONS

For testing purposes, the following experimental setup has been realized, see Fig. 3. The CYW920719Q40EVB-01 evaluation board is connected by the USB interface to a laptop Personal Computer (PC) which runs a MATLAB script for managing the signal acquisition and CS-based signal reconstruction. The ECG signal under test is a synthetic one, which is provided by using an Agilent 33220A waveform/function generator from a built-in function.

In order to evaluate the quality of signal reconstruction, the MATLAB script acquires and stores in the PC memory the raw ECG signal samples, **x** and the compressed version of it, **y**. Furthermore, the vector **p** is transmitted to the PC, together with **x** and **y** in a single UART frame.

In MATLAB, from this vector **p**, which is associated with the acquired compressed frame **y**, the **Φ** matrix is built as it is described in **Step 6**.

The reconstruction of signal $\hat{\mathbf{x}}$ is performed by using OMP algorithm implemented in MATLAB. To limit the testing time, the length of *N*=512 and *M* = {256; 128; 64; 32}, thus obtaining a *CR*={2; 4; 8; 16}, has been considered for this work. As a figure-of-merit, the Percentage of Root-mean-squared Difference (PRD) has been computed as follows:

$$\mathrm{PRD} = \sqrt{\frac{\sum_{n=1}^{N}[\mathrm{x(n)}-\widehat{\mathrm{x(n)}}]^2}{\sum_{n=1}^{N}[\mathrm{x(n)}]^2}} \times 100\% \qquad (1)$$

In Fig. 4.a) the vector **p**, red line, obtained by comparing the absolute value of the ECG signal processed as in **Step 3**, the blue line, with a threshold value of 50 mV is depicted. This vector consists of one when the signal is higher than the imposed threshold value, zero in other case.

For graphical visualization purposes, the vector **p**, which contains one and zero values, has been scaled by a factor of 1000.

The obtained compressed samples, **y**, are plotted in Fig. 4.b). The obtained vectors are compatible as it was expected.

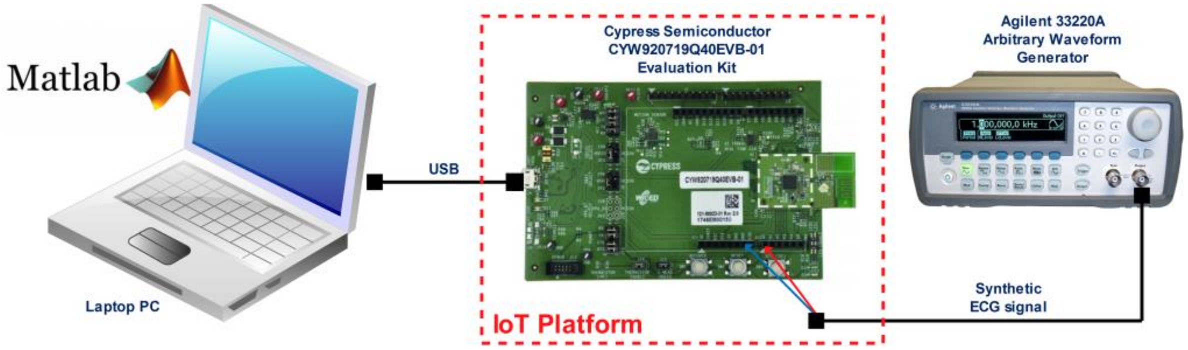

Fig. 3. The experimental setup.

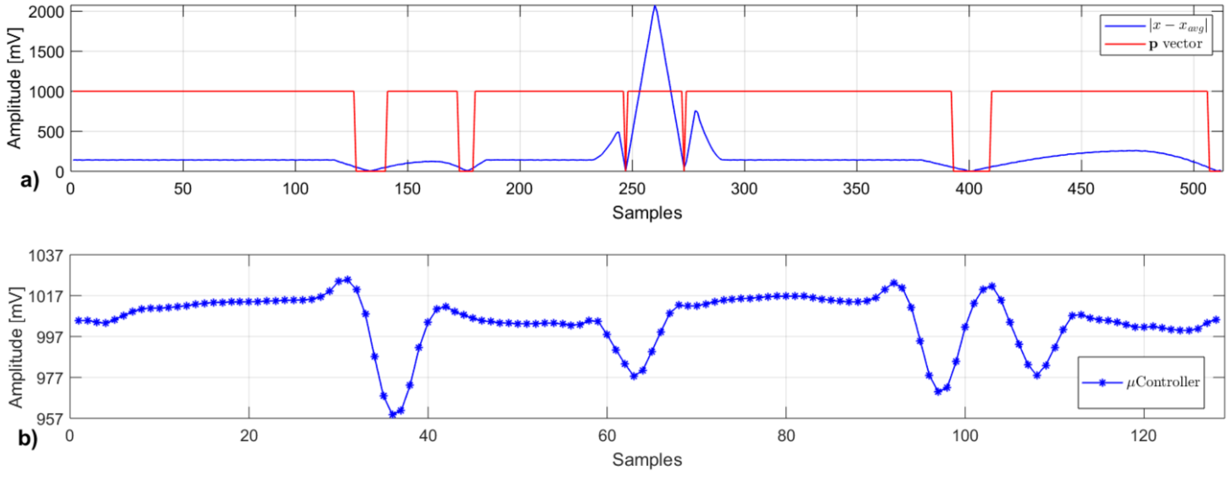

Fig. 4. Exemplification of the CS-based ECG signal sampling by its evaluation in MATLAB: a) the vector p, red line, and the absolute value of the ECG signal processed as in Step 3, blue line; b) the compressed values provided by the microcontroller

The used CR is 4. The reconstructed signal $\hat{\mathbf{x}}$ which was obtained from the compressed samples y, provided by the microcontroller, is depicted in Fig. 5.a). In particular it is possible to observe that the estimated signal approaches the original sampled one. Furthermore, in Fig. 5.b), the relative error in percentage between the reconstructed signal and the original one is reported. Thus, in this example, the maximum obtained relative error in percentage is around 8% of the original one.

In order to assess the performance of the implemented CS-based method, the PRD has been evaluated for each acquired frame by considering several CR values.

In Fig. 6, the mean value of PRD obtained for 100 trials for variation of CR={2; 4; 8; 16} is presented. From this figure it is possible to note that according to a maximum acceptable PRD value of 9% [12], a CR of 8 can be chosen for medical diagnosis purposes.

V. CONCLUSIONS

In this paper, a preliminary experimental assessment of a novel CS-based ECG signal acquisition method, which has been implemented on an IoT prototype, was presented.

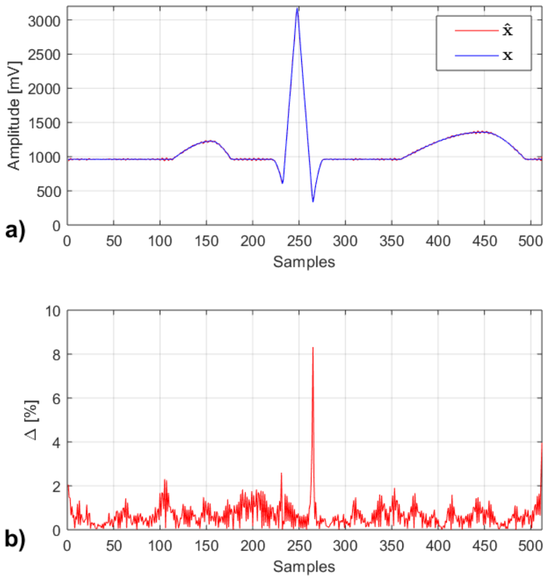

Fig. 5. One frame of ECG signal: (a) the classical sampling vs. the reconstructed signal, (b) the relative error in percentage (Δ) between the classical sampled signal and the reconstructed one.

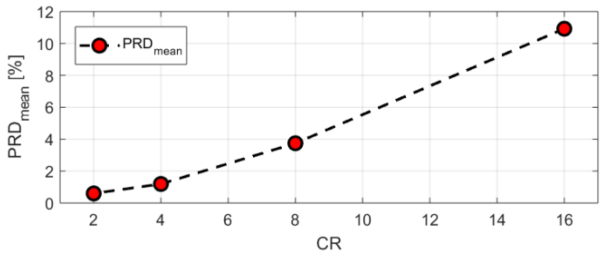

Fig. 6. The mean value of PRD results obtained for variation of CR={2; 4; 8; 16}.

The primary motivation of the presented work is to investigate the amount of samples reduction prior to transmit/store actions. The obtained experimental results demonstrate that the adopted method could provide good ECG signal quality after its reconstruction process. Thus, it was investigated the PRD as a main figure-of-merit and it was observed that even for compression ratio of 8, the method allows a good quality of signal reconstruction for medical diagnosis purposes.

Further works are directed to: (i) test the method by using raw ECG signals coming from a patient which are collected by an Analog-Front-End (AFE) module, (ii) implement a firmware which enables the BLE 5.0 capabilities of the CYW20719 SoC, and (iii) compare the energy consumption of the CYW920719Q40EVB-01 evaluation board by adopting the proposed CS-based method against raw data acquisition.

VI. ACKNOWLEDGMENT

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