"POLITEHNICA" UNIVERSITY OF BUCHAREST
ETTI-B DOCTORAL SCHOOL

Contribution in use of Wireless Sensor (WS) for Medical Monitoring Application

PhD Thesis Summary

Advisor
Prof. Emeritus Dr.
Ing. Vasile LAZARESCU

PhD Student
Ing. Marius–Corneliu ROSU

Bucharest 2017

Abstract

We'll never know it all, important is to understand something of this life!

Today it is acknowledged that a Wireless Sensors Network (WSN) it is suitable to increase the Quality of Life (QoL) for all those diagnosed with chronically Cardiovascular Disease (CVD). Complete and complex monitoring systems enable continuous observation of patients; shortcoming is the fact that affects patient's mobility due to cable connection to those devices, while it must lie down on a bed in order to be monitored.

In order to avoid this drawback, a new philosophy was developed in last years: A built-in low-power, small-sized and low-cost device solution, remotely available and able to give information in real time. Solution is obviously interdisciplinary; boundaries are related to conception and design skills of engineers, with medical and biological sciences for health care treatment purpose including diagnosis, monitoring, and therapy. *Medical Technology* ranging from clinical equipment to remote monitoring devices and micro-implants is branch and domain of this work. The entire above are related to *Medical Engineering (ME)* that exists, as History says, for centuries, perhaps thousands of years.

The goal of this work is to contribute on knowledge in use of Sensors in medical field area, and to provide to a remote authorized observer at any moment, the status of the monitored patient.

Nu le vom sti niciodata pe toate, important este sa intelegem ceva din aceasta viata!

Astazi este recunoscut faptul ca Retelele de Senzori Wireless (RSW) sunt adecvate in creșterea calitatii vietii tuturor pacientilor diagnosticati cu boli Cardiovasculare cronice. Sisteme complete si complexe de monitorizare permit observarea continua a pacientului; deficienta lor totusi consta in faptul ca afecteaza mobilitatea pacientului, datorita cablurilor de conexiune si imobilizarii la pat in timpul observatiilor.

Pentru evitarea acestui dezavantaj, in ultimii ani s-a dezvoltat o noua filozofie, si anume: O soluție ce ofera dispozitive cu consum redus, de dimensiuni mici și ieftine, accesibile de la distanta si capabile sa furnizeze informatia in timp real. Soluția este evident interdisciplinară; granitele interpatrund conceptele și abilitățile inginerilor in proiectare, cu stiintele medicale si biologice in scopul ingrijirii sanatatii incluzand diagnosticare, monitorizare si terapie. *Tehnologia medicală*, ce variaza de la echipamente clinice la dispozitive de monitorizare la distanță, precum si micro-implanturile, este domeniul de interes al lucrarii. Toate cele enumerate mai devreme fac referire la *Ingineria Medicala* care exista, asa cum istoria o arata, de secole sau poate de mii de ani.

Scopul lucrarii este de a contribui la cunoasterea utilizarii senzorilor destinati domeniului medical, pentru a oferii unui obsevator autorizat, in orice moment, la distanta, strarea pacientului monitorizat.

Contents

1. Introduction

1.1 Presentation of the PhD domain

The PhD Thesis has obviously an interdisciplinary character, related to *Medical Engineering*, covering a wide range of areas. Conceptions from Electronics, Medicine, Information Technology and Signal processing are fundaments in this work. The development of *Medical Devices* ranging from clinical equipment remote monitoring devices and micro-implants, know as *Medical Technology*, is the domain of interest in this work.

1.2 The purpose of the thesis

Generally *Medical Devices* are used for two purposes: 1.Illnesses diagnosis or other conditions on the patient's, and, 2.Prevention, maintaining or treatment of illness. Thesis is linked both purposes. Wireless Sensors (WS) for remote monitoring of Electrocardiogram (ECG), vital information for chronically CVDs, is the domain of interest addressed, with the following objectives:

1st –Design of a tiny physical interface module for long-term ECG biomedical signals monitoring. Solution must comply with requirements of a compact and low power system, and compatible with an existent portable Sensor Node (SN), with wireless capabilities.

2nd –Proposing and Achieving a filtering concept for the remote monitoring device, so that the Signal/Noise Ratio (SNR) to be improved in the obtained ECG signal, and thus be useful for those skilled in cardiology.

3rd – Carrying out real tests and setting up the optimal conditions of realized module, for raising the operating autonomy, without impacting SN parameters.

1.3 Thesis Content

Thesis is organized in eight chapters; the work content it is summarized as follows: *Chapter2* reveals the background of the entire work in this thesis. *Chapter3* §3.1, introduces in signal processing, and in §3.2 are described type of noises, fundaments of ECG processing and filtering methods. Conclusions are pointed out. In *Chapter4* specific of Biosignals and Wireless Sensor issues are discussed: Acquisition, Classification and biosignal Model, while wireless capabilities, wireless Standards in Medicine and future model proposal are approached; conclusion end chapter. *Chapter5* presents the Sensor Concept for the Medical Application, namely: General conditions, considerations for Data Acquisition System (DAS), Sensor Node (SN) and Health module (DASMedy), and running simulation for own designed ECG signal circuit. Conclusions of chapter are done. *Chapter6* first expose advantages of home monitorring and Wireless Body Area Network (WBAN) requirements, performances of achieved module DASMedy, noises in ECG, removal and new approach techniques, while in second part the obtained results with proposed denoising method; conclusions highlight adopted solution, showing that simplifies working algorithm of sensor compared to other methods, and lifespan can be extended. *Chapter7* first discuss sensors wireless connectivity, addressing and routing protocols; flow charts and practical results in wireless connection are exposed. Conclusions analyze the proposed solution in wireless connection. *Chapter8* summarizes all conclusions and results of the thesis, presents own contributions and directions of inquiry for the future work; also a list of original papers.

2. Background and Literature Review

Chapter2 include first basic concepts for Wireless Sensor Network (WSN), then concepts and considerations over WSN are given emphasizing their advantages over the traditional methods of healthcare monitoring; it is explained the source of the adopted topic and aim of this thesis; WSN major applications are described. General considerations and architecture for a Wireless Sensor (WS) are pointed in chapter, as well as WSNs architecture for ZigBee communications protocols. Literature review, glance statistics, WSN history, and a briefly State of the Art for WSNs healthcare, point the contributions of the work. Conclusions are done.

3. Theoretical considerations for Biomedical Signals filtering

In *Chapter3*, the reader is introduced into the basics of theory and methods for the signals filtering. Before to be provided to the physicians, signals must be denoised by filtering methods that cleans the numerous artifacts. The aim of ECG filtering is to improve the records accuracy against different types of artifacts and in the same time, to detect the heartbeats, to lead basic measurements of wave amplitudes and durations, and compress the data for efficient storage or transmission. In §3.1 an overall definition for signals processing I described and exposed it at all levels, while in §3.2, I started by describing briefly specific filtration methods for the ECG signal with the characteristics issues into it processing. Concluding, the interferences, artifacts, and noises have a bad influence in biosignals, which are by definition weak. Filtering methods for the small noises in ECG is still a challenge.

4. Sensor Networks with wireless capabilities

Wireless networks for medical applications improve the access and quality of healthcare for patients, saves money for healthcare providers, and are preferred for them accessibility and mobility. Chapter is dedicated to issues concerning devices able to record signals from inside human body that are important in medical diagnosis, monitoring and subsequent therapy, and transmit them wirelessly. In §4.1 are shown the diversity, classification and types of biosignals, that leads in a description of a physiological phenomenon; first methods in biosignals acquiring used by Hippocrates of Cos and description are pointed also. Standards for wireless communications in medicine are described in §4.2 and Table4.1 illustrates the main wireless protocols for medical monitoring, dedicated to WS with low power consumption and compatibility in networks. Description of available or developing medical devices, optimal rules and technical conditions, advantages in wireless technologies and demand for wireless medical applications are treated in §4.3. Conclusions show that network technology has potential to improve the Quality of Life (QoL).

5. Experimental Concept of the Sensor dedicated to the Medical Application

A report published in 2008, highlighted the demographic outlook in Europe over the next 50 years: Number of older people will increase steadily and consequently their need for medical assistance. Therefore, skills to problems brought by this reality become a necessity.

5.1 General considerations for medical application

Opportunity to work at home or office under medical surveillance is important argument for potential beneficiaries that exceed 55 or less. Solution must effectively reduce the number of hospitalization days by transferring at home the surveillance of patients diagnosed CVDs. For active people, this is a warranty that in an emergency, medical assistance is available in the shortest time. Such systems allow also decreasing hospitalization period. Idea was adopted and exposed in [RoP13] and developed later in [ROP13].

Portability is at this moment a hot topic; projects, like FP7, are launched with complementary topics e.g.: Textile medical sensors or flexible, and metallic or nonmetallic. 2008 can be considered as the reference year for the beginning of portable sensors as they are today known.

5.2 Defining the medical application

The ECG, a diagnostic method for arrhythmias, conduction abnormalities, ventricular hypertrophies, etc., is the parameter of interest for the medical application.

Physiological considerations for ECG consists of two mechanical events of the cardiac cycle having an electrical substrate, namely *the systole* and *the diastole*, corresponding to depolarization (P wave and QRS complex) and repolarization (T wave). Electrical potentials associated are recorded on thorax surface, heart being considerate an equivalent generator.

Measured parameters consist in determining of duration and amplitude of elements that define morphological and functional features of myocardium, whit respect to electrical events in heart which start from SA node, pass through AV node, Bundle of His, ending in Purkinje fibbers; active frequency of the whole heart normally is setup by SA node.

Mathematical Modeling: Whereas electrical potential of the heart is the ECG genesis, two properties of heart tissue were used to investigate potential and current distribution, in an idealized axon model equivalent circuit depicted in [MaPL95].

Experimental setup consists in wearing a WS equipped with local processing capabilities that collect and transmit ECG to a coordinator node; only a few parameters will be tracked in detection the anomalies (e.g. pulse, R -R distance).

5.3 The Data Acquisition System (DAS)

It can be configured in different architectures and depends on requirements. The experimental system adopted is only on a single channel, and it consists of dedicated electrodes/sensors for bio-potentials, block of conditioning and ECG signal filtering, acquisition module interface with Analog Digital Converter (ADC) and transceiver (ZigBee protocol), and a remote PC.

5.4 The Sensor Node

The sensor node is already realized and it has been designed so as to be able to measure and other parameters, e.g. environmental. Main components are:

The Microcontroller with following requirements necessary in his choice: *Low power consumption*, *Own internal memory size* (allows primary processing), *I/O interfaces* (various communication), *Satisfactory processing speed*, *Lower switching times* (active at hibernation).

The Radio transceiver allows wireless connections and it consumes the largest amount of energy. The use criteria [SAS01, HIL03] are: *Modulation type* (noise sensitivity as low as possible), *Transmission range* (minimal transmission energy consumption), *Transmission rate* (depend of protocol and modulation type), *Communication interfaces* (connection into sensor) *Switching time* (as small as possible). ZigBee transceivers will be used.

Power Source makes possible in independent use of medical applications sensors, outside of hospital. Solutions are chosen based on battery lifetime [ENE], thus lithium technology meets that requirement; for experimental purposes, I used Alkaline LR6 batteries.

The Temperature Sensor is important in maintaining the device parameters; an overheating can affect them performances. Also consumption in active mode is important.

5.5 The module for Health Purposes

Block diagram of module is illustrated in the Figure5.13 [RMC14], for a 'wearable' scenario as in Figure5.21 [ROP13]; part accomplished here is conditioning signal circuit DASMedy.

The electrodes collect biopotentials at skin level, and are important link in getting quality of the raw ECG signal. Different in shapes, present certain specific characteristics and generally have same constructive parts. In [LEA] the most used models are summarized. New techniques and measurement methods have been developed in purpose to avoid wired connections.

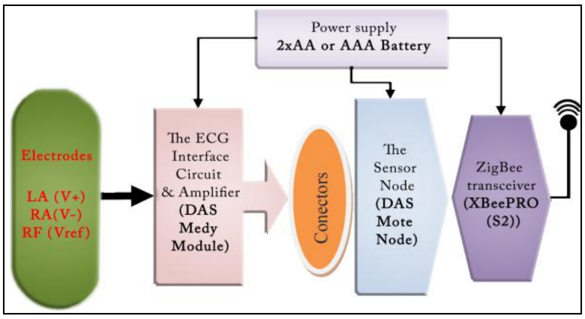


Figure5.13 *Module diagram for the own designed medical device*

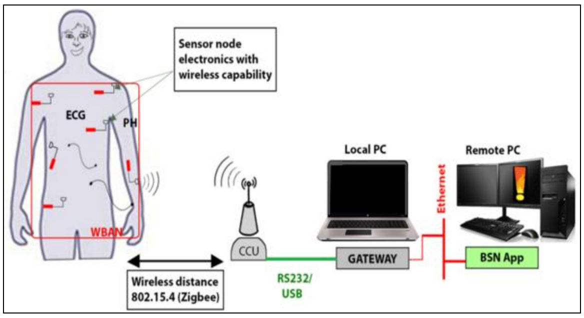


Figure5.21 *The second proposed solution approach*

The ECG signal amplifier was designed so that the values of the output signal to be in ADC module range, corresponding to Einthoven Lead I configuration. For DASMedy circuit design, I chose the 'wearable' scenario in one hop wireless connection between patient and Coordinator node (CCU) while the second via RS232/USB line, for full mobility [ROP13].

Proposed circuit diagram and running simulation is targeted towards continuous medical monitoring from a remote center. Advantages: once cardiac conditions have been established people can have a "normal" life. More applications were consulted and compared; the adopted solution for the circuit diagram must meet the proposed requirements. Proposed solution and then practically realized, is based on Texas Instruments (TI) knowledge and hardware components; TINA-TI v9 [TINA] simulation program I used to verify the future real circuit. Results illustrated in Figure5.22, show that adopted solution is feasible for hardware implementation and the components values set in simulation are appropriates and realistic; for conformity, see virtual oscilloscope. Other problems encountered: Equivalent electrical electrodes circuits (RA, LA, RL); linear function that reproduces the ECG signal on a full cycle for voltage signals generator related to RA and LA electrodes (active).

The ECG interface signal circuit named already *Data Acquisition System for the Medical signal* (DASMedy), is targeted at monitoring, with useful signal ranges between 0.5 and 35 Hz and amplitude up to 2 mV. A variable electrode-skin contact potential (hundred mV), a common-mode DC component (about 1V), muscles and respiration artifacts, and interference noises due to power line overlap raw ECG signal. The ECG interface circuit was designed separately and realized with overall dimensions of 16 x 33 mm on a double side Printed Circuit Board (PCB) [ROP13]; physical ECG hardware circuit is the one in Figure5.27 [ROS14].Signal is wired collected in the zone *,,Palmaris longus''* (LA (V+) and RA (V-)) and in *,,Tibalis*

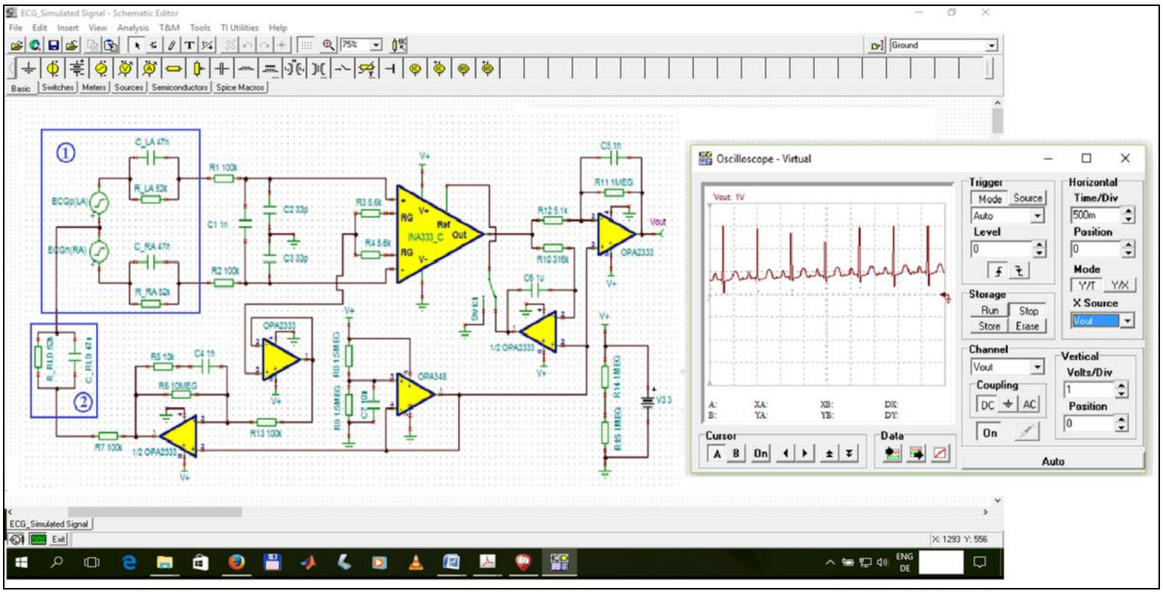


Figure5.22 *TINA-TI v9 Program simulation Print Screen*
Note: *Areas squares marked 1 and 2, represent the equivalent electrical circuit for Ag/AgCl electrodes*

Posterius'' ($RF(V_{ref})$) according Gray's anatomy (blue, red, and black), and measured directly on oscilloscope (yellow). Wet Ag/AgCl type electrodes were used.

Electronic components used for active parts TI and MICROCHIP manufacturers were preferred, while passive components were carefully selected in very low tolerances to achieve the desired performance. At the same time, their own internal noise was diminished.

Conclusions summarize the main points of the chapter and achievements: A new ECG conditioning signal circuit (DASMedy), for a system designed in remote monitoring of chronically ill patients. Module diagram is done (Figure5.13), useful bandwidth was set from 0.5 to 35Hz, wet type electrodes Ag/AgCl was used to record the ECG, description and comments concerning the DASMedy hardware is provided, simulations to test the functionality of proposed circuit were conducted in TINA-TI.v9 software from TI, prototype of ECG amplifier (baptized DASMedy) was manufactured separately on double side PCB as shown in Figure5.27, energy will be ensured by long life batteries, the system must preserve the full patient's mobility.

6. Denoising Methods of ECG Signal in Wearable Systems. Evaluation and Results for the ECG Monitoring System

A number of proposed denoising methods of ECG signal are analyzed and compared in this chapter, in aim to improve signal quality offered to clinicians.

6.1 General considerations

Progress in wireless communications and miniaturization has led to an explosion of Wireless Sensor Networks (WSN) focused in healthcare area. Researches are today interdisciplinary such as in Wearable and Implantable Body Sensor Networks domain (WIBSNs); Wireless Body Area Network (WBAN), a special category, are used in medicine for real-time monitorring. Two WBAN category gained ground: *1.Mobile Health Systems (m-Health)*, and *2.At Home Care* for in-home monitoring.

In-Home Monitoring Advantages Holter monitors are used to collect data (typically 24 hours) while processing and analysis is done offline; such devices are uncomfortable. Avoiding

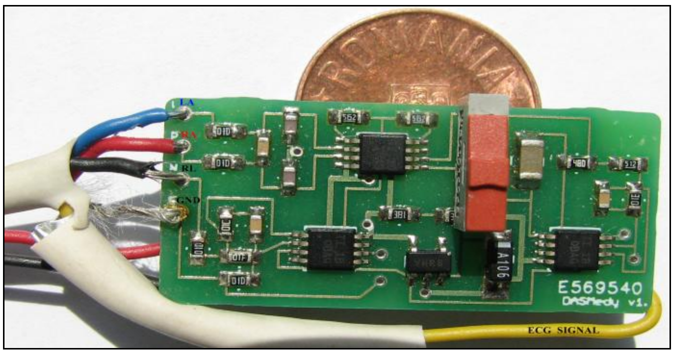


Figure5.27 *Physical prototype of the DASMedy hardware*
Legend: LA*- Left Arm;* ***RA****- Right Arm;* ***GND****-Groud*

displacement, immediate action for emergencies in real-time, continuous surveillance for 24 hours, vacancy of hospital bed combined with significant manufacturing cost reduction, are the main advantages to consider the home monitoring techniques.

The Objectives for such devices can be summarized as follow: 1.Real-time long-term ECG signal monitoring; 2.Light weight, and wearable sensor platforms; 3.Local capabilities and local memory; 4.Quick detection of the patients' heart condition.

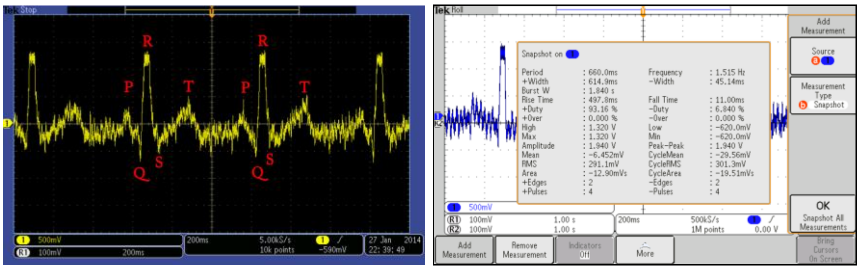
WBAN's for ECG signal are designed to measure, record and display in real-time the ECG signal without limiting the patient mobility. As was defined in Chapter5, DAU for ECG is the WS himself, a wearable device consisting of three parts: 1.The WS core, 2.DASMedy - ECG conditioning signal circuit module, and 3.XBeePRO (S2) - wireless transceiver.

Preliminary testing was measured on oscilloscope direct from DASMedy module - yellow wire in Figure5.27. For monitoring applications, bandwidth 0.5 -35Hz has been considered in further processing. Figure6.1 shows measurements [RMC14], and validity of the model simulated with TINA-TI.v9 is proven. Peak-Peak 1,94V amplitude value was obtained in a single-stage amplifier, and is great for energy consumption and further signal processing's.

6.2 Still important challenges in ECG analysis

On the subject of choosing the processing algorithm for ECG signal, challenges are still at the forefront and issues have been partially settled. The challenges that still require attention are:

P Wave Identification- having features of low amplitude, detection is important for the atrial activity with which is connected; **QT interval Estimation** is an acute subject since QRS pattern, ST segment and T wave are in permanent change due to variable Hart Rate; **Ischemic and nonischemic detection within ST changes** is still unclear especially in silent ischemia. Changes in the ST interval are related and to body moving, and electrodes change the relative position compared to the heart leading to variation of ST segment. **Beat classification in long term monitoring** encounter problems of Hi-Level noises that overlap the ECG signal, usually related to muscle or movement. Another problem is skin- electrode contact degradation leading to worse SNR and by default of P wave detection. **Reliable signal filtering and noise separation** occur with muscle artifacts or fetal-maternal ECG; filtering methods based on patterns have shown good results. **Wrong placement or electrodes moving** lead to wrong



(a) *(b)*

Figure 6.1 *ECG waveform and measured values*

a) Waveform obtained with DASMedy; b) Measured values for the waveform detection or wrong classification. **Reliable measurements** are associated with the estimated parameters; the "confidence level" becomes important for returned values of an algorithm. **ECG real data** could not be achieved, so more experiments to verify if obtained parameters will give more information than traditional ECG measurements are needed. **ECG diagnosis: Mapping parameters or values for disease prediction** is based on neural network. Due to the ability in extrapolation of the small training sets, these become sensitive on sizes distribution and outliers. **Context analysis in a global model** supposes patient's disease history. For feature recognition and classification purpose, Hidden Markov, Kalman filters or the Bayesian models classifiers are recommended. **Closed loop systems** are used in parallel with conventional internal cardioverters. Despite progress, further efforts are needed to detect atria fibrillation to ensure patient safety. **Sensor fusion** always improves the performance of an algorithm by multidimensional analysis of signals and collecting information from other sensors, reducing so the risk of false alarms. **The reconstruction problem** is known that has not only one solution. Recent ECG models have been shown to be useful for this purpose.

6.3 Electrical Potential Sources in ECG

ECG Basics refers at a standard ECG plot [BME], and how to calculate the derivation types in ECG [EET]. Electrical charge of cardiac cell membranes can be detected at skin level.

ECG Characteristics refers to ECG signals sources in purpose to design the signal acquisition hardware. Figure6.3 shows ECG signal electrical characteristics.

A Healthy Heart refers to a normal ECG like in [BME]. Entire range in ECG signal is damaged by various artifacts which jamming the useful signal. In filtering strategy, above observations are useful.

6.4 Types of Noises

The ECG signal is small in amplitude and very sensitive to noises. Abnormalities could be due to pathological conditions or due to different types of artifacts as follow.

Interference of Power line refers to parasitic field generated by Alternating Current (AC) with 50/60Hz frequency, causing problems to signal portions in low amplitude.

Electrode - Skin Noises is manifested through so called electrode pops, present two disparate waveforms of electrical potential between skin and electrode.

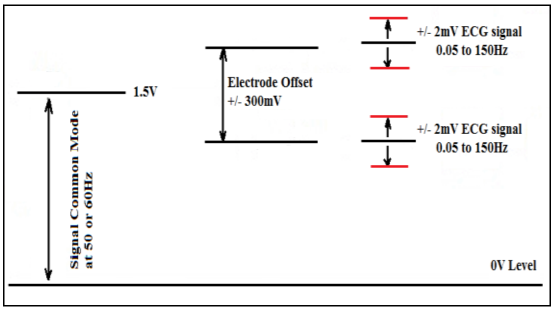


Figure6.3 *Electrical components of ECG*

Movement and Muscle contraction Artifacts parasite the useful signal by random signals; these artifacts can imitate Baseline Wander (BW) and may be confused with atrial fibrillation.
Baseline Wander(BW) is component with large bandwidth of low frequency caused by Perspiration, Respiration and Body movement, or of high frequency in tests stress.
Instrumentation noises are internal noise generated in the electronics devices; it can be minimized by paying attention to components quality.

6.5 Noises Removal Techniques from ECG

In this paragraph, methods and measures to diminish the effects of artifacts mentioned in §6.4 are analyzed. Techniques must preserve the desired information in signal, and must to take into account distortions that may arise during filtering. Attention is needed for QRS influence to output response of the filter, which is seen as a big boost that must be mitigated. In most front-end circuit, are included (LP and HP, sometimes Notch) analog filters as a first denoising step; digital filters returns accurate results and avoid nonlinear phase shift. A lot of digital filtering ways are proposed depending on the outcome and type of noise, as follow:
1. A **Notch** centered to the 50/60Hz is classical mode for *Power line noise*. A comb filter was done in [PAJ12]; another approach, a pair of complex-conjugated zeros, is done in [CSE].
2. A method with cutting frequency of 0.5Hz is suggested in [USC] for *Skin-Electrode Noise* filtering, which is very high in amplitude.
3. **Ensemble Averaging** is technique that can be used for *Muscle noises* removal, which overlaps the entire ECG signal. It shall be limited to the beginning to a single QRS morphology for good results, requiring more beats for become available; in [RSR09] other technique is described. However, muscle artifacts still remain open question due of filtering distortions.
4. **Linear Filtering** with *Time-Invariant* for hardware or software implementation [EET, CSE], and *Time-Variant* method usually for stress tests with „Prevailing Heart Rate” (PHR) implementation, are principal two filtering approaches for BW Noises, low frequency components, generated by offset electrodes voltages, respiration, and body tremor. **Polynomial Fitting** is the second option, and consists in selecting the points from a „silent” segment (best choice PQ interval); higher-order polynomials it means high compute cost [CSE].
5. Today the task for components producers is *Instrumentation Noises* problem. Instrumentation amplifier constituting the heart of DASMedy, in respect to SNR and CMRR, must operate in an optimal range.
Apart classical techniques, two different approaches are further analyzed.

6.6 Processing with Wavelet Transform (WT)

A „Supervised learning” method type in which basis functions are chosen priori; overview in [ADD02, ADD05, MER05, SKK13].

Theoretical Approach is based on deterministic component of cardiac activity. In classical methods both components signal and noise are not deterministic, so results in ECG filtering are with low performances. To cope with the temporal change must be used simultaneous time-domain and frequency-domain signal analysis. Generalized time-frequency distribution for a signal with a kernel function is given by [COH95]:

$$C(\omega,t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\varphi(\gamma,\tau)x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})e^{-i\omega\tau-i\gamma(\theta+\tau)}d\theta d\tau d\gamma \tag{6.1}$$

When $\varphi(\gamma,\tau)$ =1 equation (6.1) is the Wigner-Ville distribution, giving good resolution in time and frequency. Based on that, WT constitute a special approach in ECG signal processing and execute superior time-frequency localization by choosing a function with characteristics similar to ECG signal. For signal *x(t),* WT is defined as follows:

$$Wax(b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}x(t)\psi\left(\frac{t-b}{a}\right)dt, a>0 \tag{6.2}$$

WT use φ = *Scaling function* and Ψ = *Mother Wavelet function,* with $\Psi(t)$ average:

$$\int_{-\infty}^{+\infty}\psi\left(t\right)dt=0 \tag{6.3}$$

WT of *x(t)* at scale *a,* and $\Psi(t)$ function with origin in $\varphi(t)$ smoothing function, is:

$$Wax(b)=-a\left(\frac{d}{db}\right)\int_{-\infty}^{+\infty}x(t)\varphi a\left(t-b\right)dt \tag{6.4}$$

with scaled version of smoothing function:

$$\varphi a(t)=(1/\sqrt{a})\varphi\left(t/a\right) \tag{6.5}$$

Changes made by WT over the signal must be only in time and shape must remain unchanged; this goal is accomplished by choosing appropriate basis functions. Is a Multi-Resolution function that ‘unfolds' the non-stationary signal, selected in a manner to satisfies the requirement of viewing of both frequency features, the high level and low level of the signal. Correlating with raw ECG at several scales, important details of signal are obtained. Criteria mentioned above is fulfilled by Daubechies order 4 (Db4) Stationary WT (SWT) function, morphologically resembling with ECG signal [DbW].

6.7 Analysis with Hilbert–Huang Transform (HHT)

Is a Joint Time-Frequency Analysis (JTFA) technique, in fact transformation of *N*-point into an *M*-dimensional signal (for ECG *M*=1), based on Empirical Mode Decomposition (EMD). Second component of HHT is Hilbert Spectral Analysis (HSA). HHT is a nonlinear and non-stationary data analysis.

EMD is the main key in HHT; assumption- data may have several simple ways anytime, coexisting with very different oscillation frequencies that overlap, attempted and verified in empiric manner. Complicated component or data set can be decomposed in Intrinsic Mode Functions (IMF), small and finite. Method is adaptive, efficient, and applicable to processes time-frequency-energy. Proprieties and algorithm are described in [HUA98, HUS05].

HSA is based on frequency and instantaneous amplitude found in a signal, an alternative to paradigm 'time-frequency-energy'. Complete description and consideration in [HUA98].

Properties of HHT have been demonstrated empirically by tests and done in [HUA98]. In almost cases, the HHT returned results much clearer than traditional analytical methods.

6.8 Noise Removal results

Because wearable systems are limited hardware and software, tendency is for advanced software in ECG processing to be in remote monitoring centers; accurate filtration are important.

Materials and Methods: Experiments have been carried out in Uni's Laboratories, platform being powered by batteries. The wave shape result obtained is illustrated in Figure6.1; signal was recorded on a Tektronix 3000 series oscilloscope, and used values are in table below.

Parameter	Operating voltage (V)	Stand Current ($x10^{-6}$ A)	Load Current ($x10^{-6}$ A)	Amplitude **Pk-Pk** (V)	**X** Setting (s)	**Y** Setting (V/div)	Bandwidth ($x10^{6}$ Hz)	Sampling Rate (Sampl/s)	No. of Samples	Signal shape
Value	1.8 -3.3	137	193	1.92	0.25	0.5	20	500	2500	good

Filtering techniques results demonstrated that software method is better choice, after outcome with an analog Active RC (ARC) Butterworth of 2nd order filtering attempt was mediocre. In Figure 6.18, Spectrum of Frequency (SoF) and a Spectral Density of Power (SDP) shows that 0-35Hz is the band of interest; 50Hz peak is laboratory power lines influence field [ROS14]. Waveforms were recorded primarily on the oscilloscope from subjects that sat on the chair quietly; for all outcomes I used MATLAB. Methods were focused on removing artifacts presented in §6.4 by combining techniques described in §6.5; each one involves advantages and disadvantages. Results in experimental part are done below in Figure6.19.

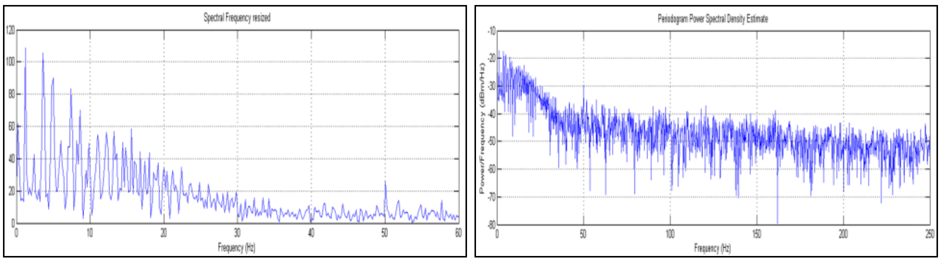
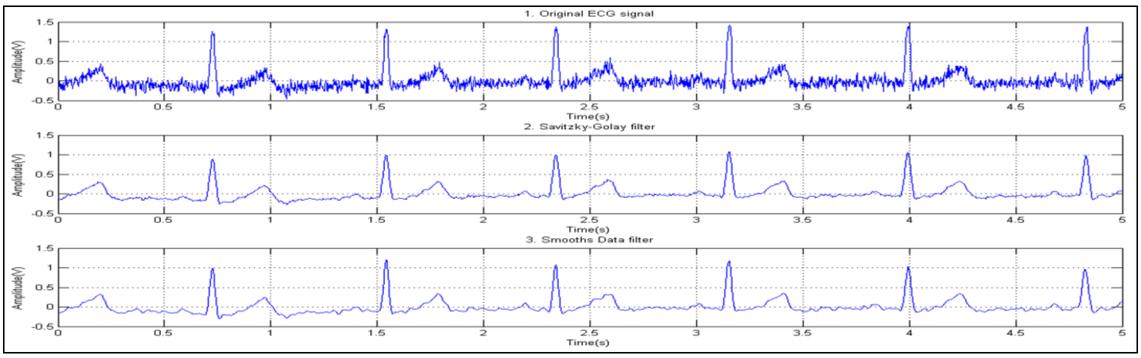


Figure6.18 *SoF and SDP for ECG signal*



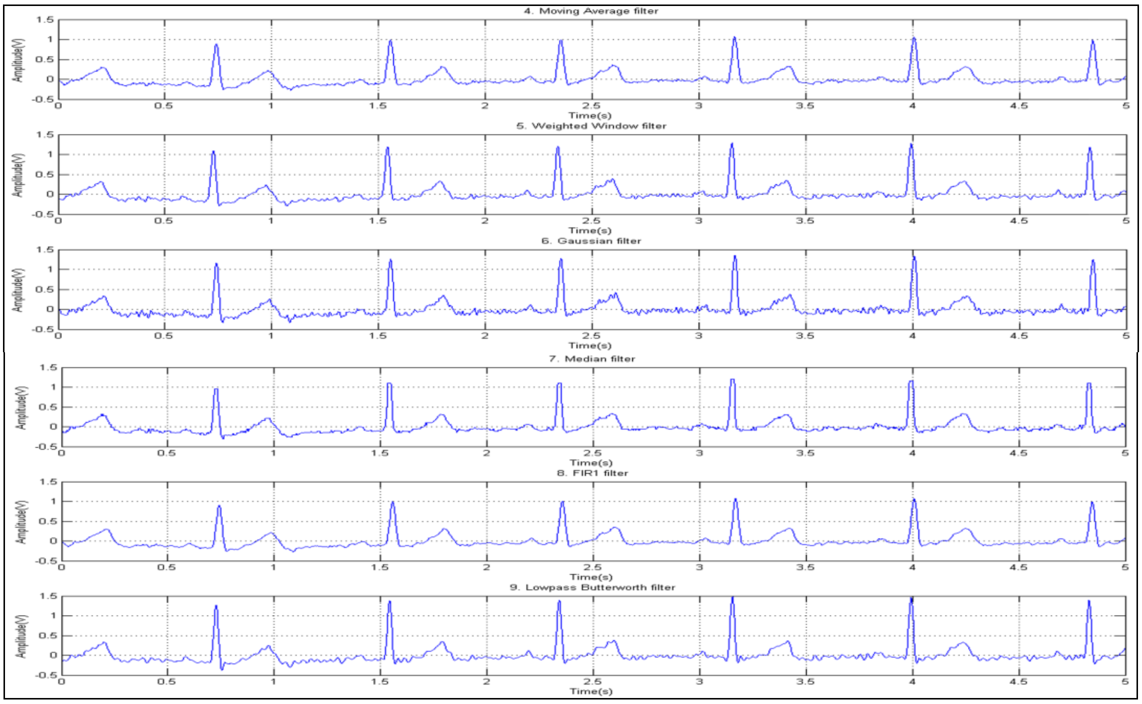
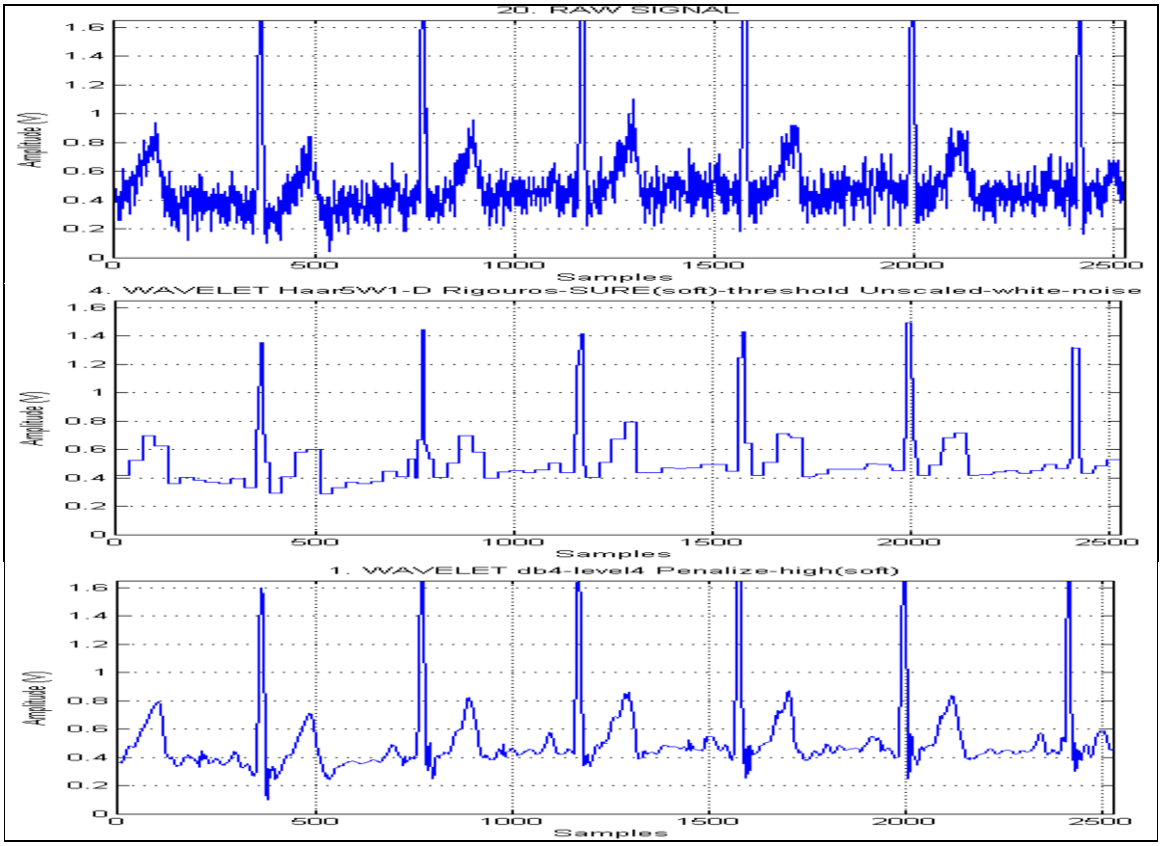


***Figure6.19** Versions of soft filtering for ECG signal*

As I stated **WT** is another approach related to ECG denoising and the encouraging results obtained show that they are appropriate to the systems limited in software and hardware resources To it both high-level and low-level signal features to be viewed, a suitable Mother Wavelet function must be chosen. Scale, the noise variance and the threshold value play important role; best results obtained are those of Figure6.20 [ROY15].



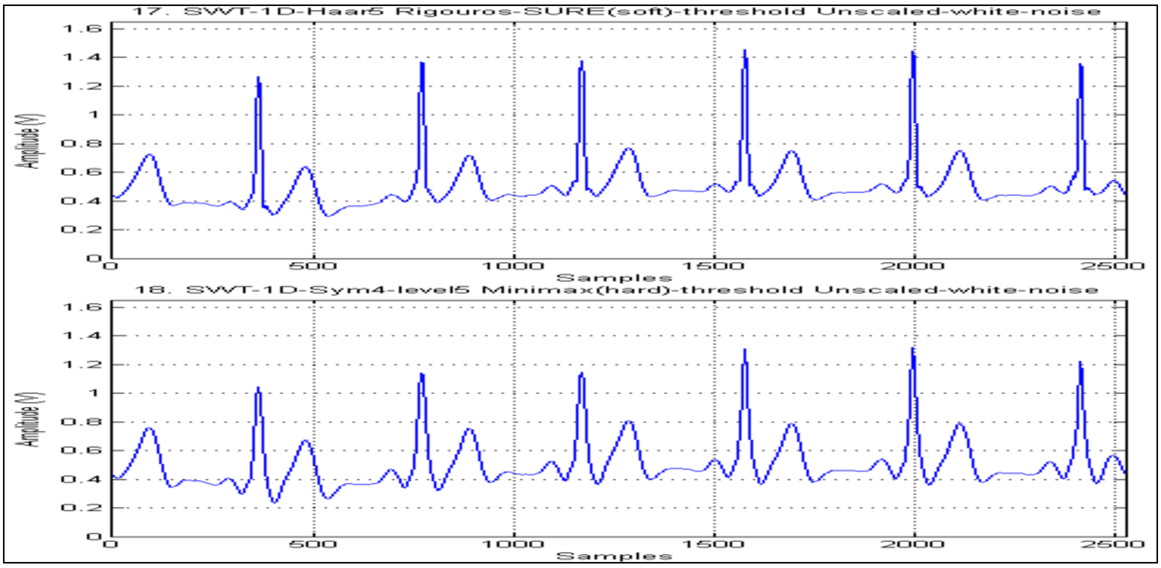


Figure6.20 *Best denoising results for Wavelet functions*

Processing in WT has advantages that ECG shape remains unchanged, only changes in time extension been allowed. The Stationary WT for one dimension (SWT 1-D) meets the above requirement, and a translation of the original signal does not necessarily imply a translation of the corresponding wavelet coefficients. Remark: When calculating the SWT, the signal length criteria (number of samples) must be considered; if length is inadequate for SWT chosen, signal must be filled - at the beginning or end of the signal - with a minimum of zero samples so that minimum length criterion be fulfilled. MATLAB warns the user. In Figure6.21 [ROS14] is show result obtained with a SWT of 5 level decomposition Daubechies order 4 functions (Db4) with specific soft values for threshold selected after several attempts; first plot in all figures is real row ECG signal. Capability of noise rejection for each type of filtering was determinate with Signal / Noise Ratio (SNR).

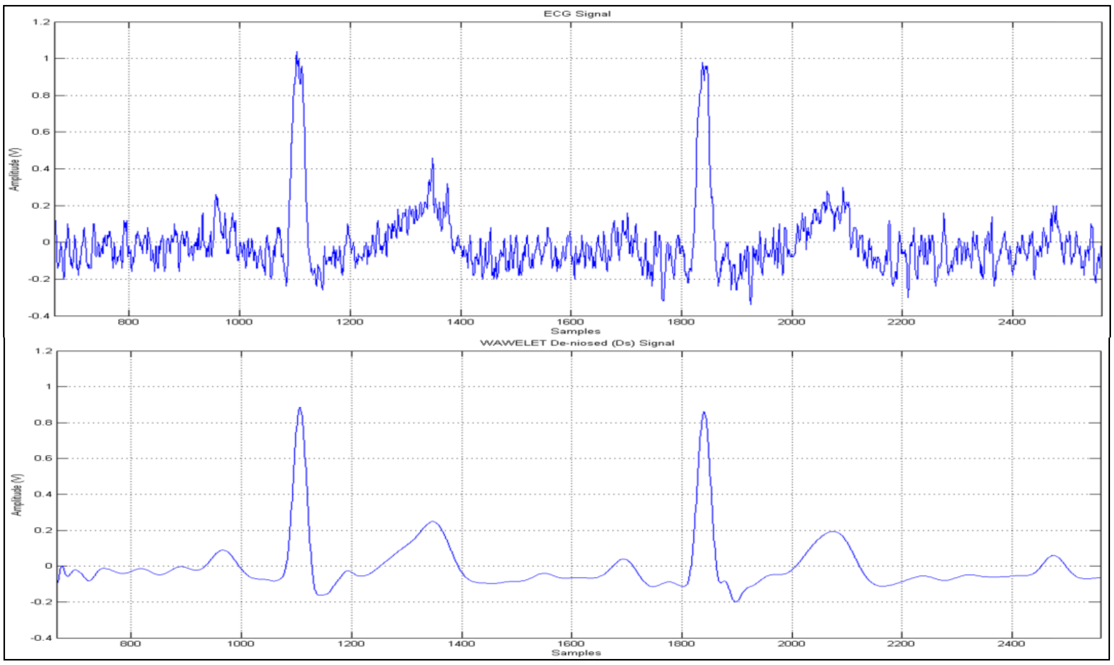
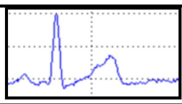
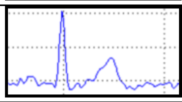
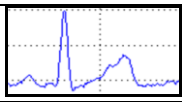
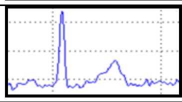
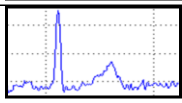
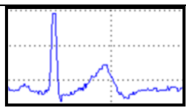
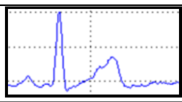
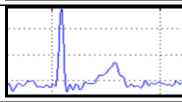


Figure6.21 *Denoised ECG using SWT 1-D*

Second special method is **HHT** algorithm that takes into account the relationship between amplitude, frequency and time. Analysis with HHT is an Ensemble EMD (EEMD) which takes as assumption that ECG has IMFs at different scales. Method carries a high computing time, better noise reduction results will perform in off-line analysis, disadvantage that should be considered.

Conclusion are summarized as follow: Choosing the appropriate parameters for denoising and decomposing ECG signal, performance in increasing the SNR will grow; but a compromise must be made between the distortion and the smoothness of the ECG signal. Table below compares suitable solutions considered for the processing algorithm. Amplitude attenuation, with reference to the QRS complex, is minimal in two cases: Butterworth and Weighted Window. Allure of the other characteristic points (P wave, T wave, and U where applicable) is tracked better or worse by filtering algorithm; quite satisfactory results are for *Savitzky-Golay* , *Moving Average*, *Median* and *Fir1* filtering method. On the other hand, a smaller attenuation of the QRS complex means a high-frequency weaker filtering; ripples that still cover P wave, which is the beginning of ECG cycle, are an obstacle to specialized software for automatic interpretation.

WT method, which is not enough explored, returned results with a very good degree of accuracy; detailed description of WT implementation I done it in §6.6 and in support Figure 6.20

Feature / **Process**	**Amplitude attenuation** (%)	**S/N** (dB)	**Time** (s)	**Accuracy**	**Shape of ECG Points**	**ECG Obtained**	**Remarks**	**Obs.**
Savitzky-Golay	27.5	5	1.5	good	Kept; clear		Flat signal portions with fewer ripples	Suitable to implement in µP.
Smoothing	24.7	12	1.4	well	Kept		**P** wave masked, ripples in flat portions	
Moving average	29.8	5	1.7	well	Kept; clear		Flat signal portions with fewer ripples	Suitable to implement in µP.
Weighted Window	11.9	3.6	1.7	Less well	Kept		**P** wave masked; ripples presence	
Gaussian	17.8	4.3	1.6	Less well	Kept		**P** wave masked; ripples presence	
Median	20.2	0.5	1.5	good	Kept		**P** wave sometimes masked; **R** point rounded; ripples	
Fir1	26.6	4.8	1.4	good	Kept; clear		Flat signal portions with fewer ripples	Suitable to implement in µP.
Butterworth	9.8	29	1.4	Less well	Kept		**P** wave masked; ripples presence	

and 6.21 demonstrates that the algorithm based on WT returns excellent results. Without doubt the SWT returned the cleanest ECG signal, and for diagnostic accuracy of ECG, frequency ranges between 0.05 to 1Hz is well preserved, in order not to lose the characteristic of the ST segment. Results are clearly superior to all other exposed methods, atenuation of QRS is comparable with cases S-G, Moving Average, Median and Fir1, but visible of high quality in terms of overall filtering. **P** and **T** waves are well reconstructed, so that application of an automatic classification process is less likely to return false results, suitable for real time wearable monitoring systems.

Processing with **HHT** carries a high computing time, for record a cycle with 5000 iterations result were returned after 3 min., so better is to use the method in off-line analysis; results of this chapter were done in papers [ROS14, ROS15, ROY15].

7. Wireless Transmission for the ECG signal

Goal is to show that small wearable devices are able to transmit in real time ECG biosignals, after transferred in digital domain. To display the signal in a remote station, a Graphical Interface (GI) written in MATLAB was performed.

7.1 Wireless connection

The traditional model is point-to-point transmission, from a source node to an end node without any retransmission. Single-hop wireless system is used where the distance between two nodes does not exceed the range of the transceivers, like in present case here.

Wireless communication techniques for sensors comply the 7-layer model Open Systems Interconnection (OSI). In laboratory experiments the channel access technology method I had used, for 1-to-1 communication link setup with fixed-allocation method for channel access with a pre-set routing protocol connection.

7.2 Methods and Wireless Test results

Setting and configuration of sensors is important, namely the XBeeS2Pro transceivers used, so that wireless link performance to be optimal. As I stated, channel access technology method was preferred for point to point wireless connection; data-link layer thru MAC protocols has the responsibility to allocate resources for this task (OSI level 2). Figure7.3 show flow chart diagrams wireless connection. XBeeS2Pro transceivers used have been configured with XCTU software utility; snapshot from Figure7.4 show real modules icons with MAC addresses (**C**- Coordinator, **R**- Router). **C** connected directly to laptop via USB was configured in API (Application Programming Interface, a frame-based method), and **R,** in fact ECG WS, was configured in AT (Transparent) mode for fast communication reasons. Collected ECG signal is analogical, and wireless transmission is digital; C communicate with GI via USB thru command *fopen(**obj**)* and ***obj*** is defined by parameters: *'#COM port', 'BaudRate'*, and

'Data-Bits'. Also should be checked which serial port it was allocated for **C**, otherwise MATLAB return error message in Command Window. Figure7.5 is physical **C** plugged to laptop. Concluding, the purpose of this chapter has been reached; a direct link between two sensors that were setup for this purpose I established in real time. Digital signal received is reconstituted accurately on GI written in MATLAB; the analog signal was constantly watched on the oscilloscope. Successful attempts I obtained inside the building over a distance of about 35m. A photo of a set of 8 (Figure7.6), demonstrate that the purposed goal in this chapter was achieved; wireless technologies is less invasive, can to improve the lives of patients, and must taking into account the requirements of limited energy resources [YAR15].

8. Conclusions

Healthcare thru WS are gaining importance considering that statistics, reports and demographic predictions are worrisome. Any method that helps to reduce costs without neglecting quality means double advantage, both for the patient as well for public system.

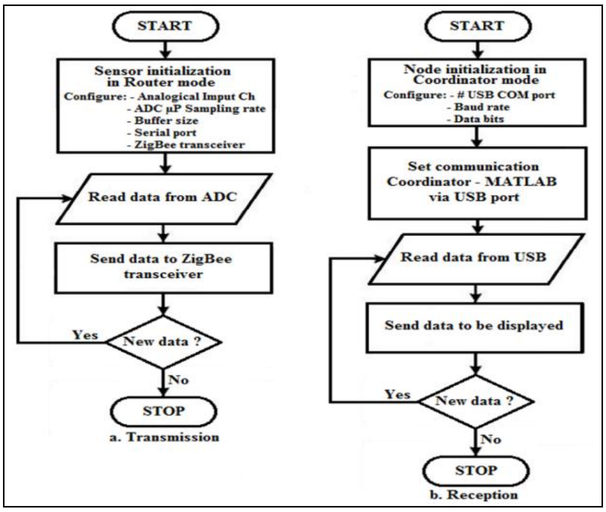


Figure7.3 *Wireless connection flow charts*

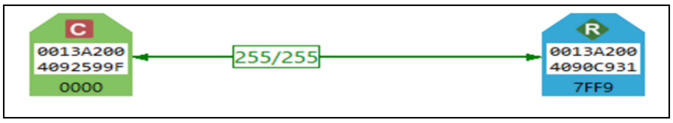


Figure7.4 *XBeeS2Pro link connection*

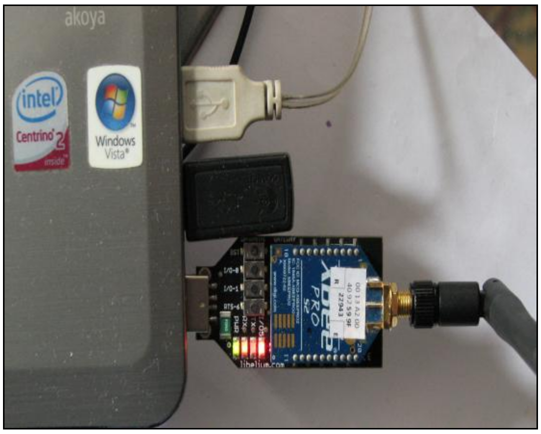


Figure7.5 *Coordinator Node plugged into laptop*

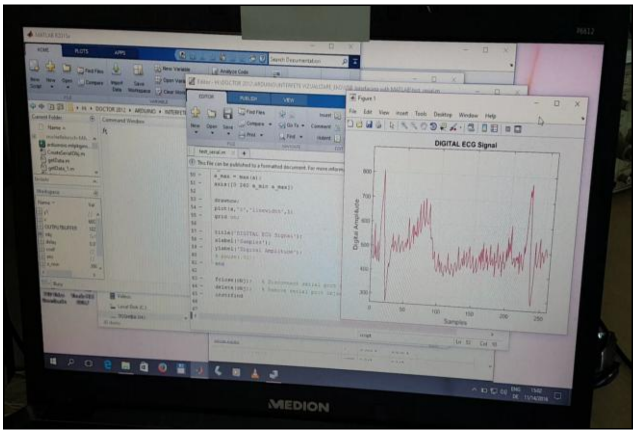


Figure7.6 *Photo of screenshots taken from video footage*

8.1 Conclusions of the thesis

This work presents the results obtained in my efforts to improve the use of wireless sensors in medical monitoring applications. Medical Sciences and Engineering Sciences represent the basic structure of thesis, the subject being of interdisciplinarity. Thesis is divided into eight chapters; apart of conclusions chapter, the other seven were described in §1.3. A large part is dedicated to Chapter 6, where research problems for healthcare applications are pointed for this kind of implementation. Grace to ECG signal is possible to measure various CVDs and abnormalities; a correct signal processing strategy lead us to a right interpretation for cardiac diseases, so distortions caused by the filter should be carefully quantified. Comparison between several methods of analysis and analytical processing revealed that only certain methods can be used for ECG signal denoising and decomposition. The new health monitoring device with respect to signal processing, take account of these:

- *Biomedical signals are weak;*
- *The influence is due to interferences, artifacts and noises;*
- *Removal of Random Noise, Structured Noise (power line influences), High-Frequency and Low-Frequency, Physiological Interferences, must be combined optimally in filtering techniques.*

WT and HHT analysis were also discussed in Chapter 6; the results are superior to all other filtering methods, and mainly two aspects must be stressed:

- mathematical calculations for both methods are laborious, especially for HHT;
- compared to HHT the WT functions returns faster results, which qualifies them for use in monitoring systems in real time; adequate choice of WT and programs developed in MATLAB, have decided for use in processing in remote monitoring center, for digital ECG signal received.

Chapter 7 shows that wireless technologies for healthcare improve the lives of patients. So, main contributions and results belong to Chapters 5, 6 and 7.

8.2 Contributions

Research, design, implementation, testing and simulation of all those listed below, I have disseminated in a total of 9 articles in journal and volumes of international conferences quoted IEEE and ISI. In applications, visualization, and results interpretation for raw ECG signals processing, I used MATLAB® environment [RMC14, ROS14, ROS15, ROY15, and RIH17].

Theoretical Contributions

1. I defined principles, place and purpose of small biomedical devices, for applications working in wireless technology to monitoring long-term ECG signal and real time; I mainly considered the design and size [RoP13].

2. I analyzed the theoretical problems of wireless technologies used in medical monitoring, considering that the multiplicity of standards and solutions available, still show and maintains a variety of concepts in this field [PAR13, ROS14].
3. Setting the CCU wireless system definition only as a Life-Sync Coordinator node, which collects ECG signal from the patient using ZigBee protocols, as advantages of continuous monitoring in a mobile environment [RoP13].
4. I analyzed the structure of key artifacts that disturb an ECG signal [ROS15].
5. Analysis, verification and validation of algorithms and schemes of digital processing for real ECG signal; results I compared with existing solutions in the literature obtained on ECG signals generated, or from specific databases for ECG [ROS14].
6. I argued simple, to the point and easy to understand, for using the Wavelet and HHT transform, in denoising approach [ROS15, ROY15].
7. Argumentation and analysis for processing algorithms less frequently used than usual, as well as and by comparing the efficiency of the methods, thru SNR [ROS14].

Experimental and Practical Contributions

1. I developed a new ‘Wearable’ hardware device as solution for ECG signal acquisition, in first lead electrode configuration according scenario from Figure 5.22; design was done so that the values of the output signal to be in ADC module range [ROP13].
2. I designed separately the final ECG hardware circuit, because the Sensor Node was already done, interlinking being realized by two connectors; this I shown in Figure 5.25 [ROS14] and for size comparison (16x33mm) I referred to a 5 bani coin.
3. I have tested and improved the features for ECG signal conditioning interface (DASMedy), using TINA-TI simulation platform from Texas Instruments.
4. I wrote and tested the software applications in MATLAB for ECG prefiltration script in digital domain, acquired with DASMedy module [ROS15].
5. I improved filtering algorithms performance targeted in order to get the shape of ECG signal characteristics of interest; I verified and chosen the WT performance as final processing method to be implemented in remote monitoring station [ROS15, ROY15].
6. I compared in term of cost function and time the noise removal results in the two special cases of processing: WT and HHT, using MATLAB dedicated tools for this purpose [ROY15].
7. I wrote the software applications in MATLAB for GI, to display the ECG digital signal for wireless transmission to a remote computer with ZigBee protocols; XCTU interface was used to setup the XBeeS2Pro transceivers [RIH17].

8. I created the hardware system so that both ECG signal, analogical and digital, to be observed simultaneously on the oscilloscope and at remote PC; a direct link connection has been established. I tested and reception attempts outside the laboratory, with promising results till 40 meters [RIH17].

8.3 Future Research Areas

There are multiple possibilities in this thesis, which could be developed in the future; main of them with immediate achievement are presented below:

- Developments of new algorithm for data compression and transmission, dedicated for MSP430F2 microprocessors, so that criterion of minimum power consumption in sensor to be fulfilled; effectiveness evaluation will be conducted at the level of a WSN in star architecture, composed for the beginning, of four nodes attached to patients configured as *Router* or *End-Point*, and a *Coordinator* node linked to PC via USB.
- Development of a new GI, for the assessment requirements mentioned above with at least two channels of simultaneous display for remote monitoring station; it must also confer the possibility to those skilled in cardiology, to select the parameters of interest for a more accurate evaluation of the patient.
- Extension and application deployment at a specialized department of one hospital since and today is still used Holter monitoring; also the service life can be evaluated over an extended period, in real operating conditions.
- Also must be taken into account and the commercial face of the end product and Quality/Price Ratio, and a solution in effort to reduce the wired connection inconvenience.

References

[ADD02] Addison, P. S., “The Illustrated Wavelet Transform Handbook: Introductory Theory and Applications in Science, Engineering, Medicine and Finance”, 1st ed., CRC Press:2002.

[ADD05] Addison, P. S., “Wavelet Transforms and the ECG: A Review”, Physiological Measurement, Vol. 26, No. 5, 2005, pp. R155–R199

[BME] http://www.classes.usc.edu/engr/bme/620/LectureECGNoise.pdf

[COH95] Cohen, L.: “Time-Frequency Analysis“, Prentice-Hall, Englewood Cliffs, NJ. 1995

[CSE] http://courses.cs.washington.edu/courses/cse466/13au/pdfs/lectures/ECG%20 filtering.pdf

[DbW] http://en.wikipedia.org/wiki/Daubechies_wavelet

[EET] http://www.eetimes.com/document.asp?doc_id=1278571

[ENE] www.energizer.com.

[LEA] www.leadlok.com

[HIL03] Jason Lester Hill, “System Architecture for Wireless Sensor Networks”, Doctoral Dissertation, 2003.

[HUA98] Huang, N. E., et al., “The Empirical Mode Decomposition and the Hilbert Spectrum forNonlinear and Non-Stationary Time Series Analysis,” Proc. R. Soc. Lond. A, Vol. 454, 1998, pp. 903–995.

[HUS05] Huang, N. E., and S. S. Shen, “The Hilbert-Huang Transform and Its Applications”, Singapore: World Scientific Publishing Company, 2005, http://www.worldscibooks.com/mathematics/etextbook/5862

[MaPL95] J. Malmivuo & R. Plonsey: Bioelectromagnetism - Principles and Applications of Bioelectric and Biomagnetic Fields, Oxford University Press, New York, 1995, Cap.6, available on http://www.bem.fi/book/ [PAR13] Pasca, S. and Rosu, M., ‘’A new approach for Healthcare Monitoring’’. In: The 4th IEEE International Conference on E-Health and Bioengineering (EHB 2013), Iasi, Romania November 2013 (KNS article).

[MER05] Merry, R.J.E, “Wavelet theory and applications: a literature study”, Technische Universität Eindhoven, NL, DCT 2005.053. (2005) Available: http://alexandria.tue.nl/repository/books/612762.pdf.

[PAJ12] Pankaj K. Gakare, Abhilasha M. Patel, Jignesh R. Vaghela, R.N.Awale ´´Real Time Feature Extraction of ECG Signal on Android Platform´´ IEEE Conference on Communication, Information & Computing Technology, Mumbai, India October 2012

[PAR13] Pasca, S., and **Rosu, M.**, "A new approach for Healthcare Monitoring". In: The 4th IEEE International Conference on E-Health and Bioengineering (EHB 2013), Iasi, Romania November 2013 (KNS article), **WOS: 000346672900061.**

[RIH17] **Rosu, M.C**., Iliesiu, A., Hamed, Y.C., “A MATLAB Interface for Monitoring in Real-Time of ECG signal Wirelessly Transmitted”, In: International Conference on Advanced Technology Innovation 2017 (ICATI2017), Samui, Thailand, June 2017. (Accepted paper)

[RMC14] **Rosu, M. C**., ‘’ Implementation for a WBAN-ECG Monitoring System (Preliminary results)’’. In: The 14th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM 2014), Brasov, Romania May 2014, **WOS:000343551300120**.

[RoP13] **Rosu, M**. and Pasca, S., ‘’A WBAN-ECG approach for real-time longterm monitoring’’. In: The 8th IEEE International Symposium on Advanced Topics in Electrical Engineering (ATEE 2013), Bucharest, Romania May 2013, **WOS: 000332928500080**.

[ROP13] **Rosu, M**. and Pasca, S., ‘’WBAN Based Long Term ECG Monitoring’’. In: International Journal of Monitoring and Surveillance Technologies Research, 1(3), pp. 20-37, July-September 2013, **DOI: 10.4018/ijmstr.2013070102, ISSN: 2166-7241**.

[ROS14] **Rosu, M. C**., ‘’Preliminary Evaluation for an ECG Monitoring System’’, In: The 6th IEEE International Conference on Electronics, Computers and Artificial Intelligence, Bucharest, Romania October 2014 (ECAI 2014), **WOS: 000380489500014**.

[ROS15] **Rosu, M. C**., ‘’ Methods for Denoising the ECG Signal in Wearable Systems’’, In: The 7th IEEE International Conference on Electronics, Computers and Artificial Intelligence, Bucharest, Romania June 2015 (ECAI 2015), **WOS: 000370971100106**.

[ROY15] **Rosu, M.C.** and Yassin, C. H., "An Alternative Tool for ECG Analysis in WSN?’’ In: The 5th IEEE International Conference on E-Health and Bioengineering, Iaşi, Romania, November 2015 (EHB 2015), **WOS: 000380397900219**.

[RSR09] M. Z. U. Rahman, R. A. Shaik and D. V. R. K. Reddy, “Noise Cancellation in ECG Signals using Computationally Simplified Adaptive Filtering Techniques: Application to Biotelemetry,” An Int. J.(SPIJ,) vol. 3, pp.120-131, 2009.

[SAS01] C. Schurgers, O. Aberthorne, and M. Srivastava, “Modulation scaling for energy aware communication systems,” Proc. of the International Symposium on Low Power Electronics and Design, Huntington Beach, CA, pp. 96–99, Aug. 2001.

[SKK13] Stojanović, R.; Knežević, S.; Karadaglić, D. and Devedžić, G., “Optimization and Implementation of the Wavelet Based Algorithms for Embedded Biomedical Signal Processing”, Proc. in: Computer Science and Information Systems 2013, Vol. 10, Issue 1, p.: 503-523, doi: 10.2298/CSIS120517013S.

[TINA]http://www.ti.com/tool/tina-ti

[USC] http://www-classes.usc.edu/engr/bme/620/LectureECGNoise.pdf

[YAR15] Yassin, C. H. and **Rosu, M. C.**, ‘’ Energy-Saving Strategies in Monitoring for Wireless Sensor Networks’’. In: The 21th IEEE International Symposium for Design and Technology in Electronic Packaging, Brasov, Romania October 2015 (SIITME 2015), **WOS:000377765500045**.