Politecnico di Milano
Scuola di Ingegneria dell'Informazione

Polo territoriale di Como
Master of Science in Computer Engineering

ECG-ira: An efficient mobile app for ECG analysis

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Abstract

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Chapter 1

Introduction

ECG-ira stands for ECG (electrocardiogram) instant rapid analyzer and it is an android application developed for the acquisition, visualization and analysis of the electrocardiogram signals. The application acquires and stores the record from the zecg acquisition device (using the zecg device format) property of the Politecnico of Milan but it can also open and visualize other ecg format from other devices. Ecg-ira is part of a greater and long term project (zecg itself was part of a first step). ECG-ira aims to exploit the reliability and performance of a complex software for electrocardiogram signal acquisition, visualization and processing within a smartphone device through a mobile application. Apart of the analysis algorithm already implemented during a past thesis (by Diego Ulisse Pizzagalli), the application was designed and implemented from scratch. During the process we dealt with the devices limitation in term of performance power and limited memory. We overcome many issues, related also to small and different screen size and density of pixel, due to the great number of different devices currently on the market. We had to exploit the multithreading and efficient memory usage strategies in order to achieve responsiveness and fulfill the medical requirement for an ECG compliant application. The result is an application which is easy to use because it follows all the best design principles according to the official Google guidelines for responsive UI and UX. By taking advantage of the multithreading capabilities and the usage of all the availables cores into a device, we achieved an application which performs fast and well.
This thesis is structured as follow:

- After this introduction we give a brief but detailed overview about the heart, its functionalities and how an electrocardiogram is related to it by explaining from what its an ecg to how heart electrical signals are detected and read.

- In the State of Art chapter we show the panorama of the actual devices for an ecg acquisition and some availables application on the market which allow to open and read an ecg record.

- Then it follows the Objective chapter in which we describe and explain the goal of this thesis work.

- The Requirements chapter is where we list a set of functional and nonfunctional set of features came up during the planning phase. The final result should be compliant with all of them.

- The Problem chapter deal with all the issues related to the project development. Here we discussed about the problem of choosing a development platform with respect to another, the hardware limitation on a smartphone device and the problems strictly related to the ecg signals.

- The Solution choice chapter is where we explain and provide our reasonings to the implementation choices, from the platform choice to the programming language choice to why we decide to avoid using drawings libraries preferring a custom and proprietary implementation.

- In the System architecture chapter we provide a general overview of the project structure for both the acquisition device implementation and architecture both the mobile application structure and main functionalities.

- In the Implementation details chapter we described all the main components and Java classes. Here we provide also hint for future implementations and adaptations.

- In the Final result chapter we propose some screenshots, with descriptive captions and description, of the main screens of the application; then we go through a performance analysis of application by observing how it affect the memory, the cpu and the response time of some portion of the code. The test were conducted on many different devices but only data from the older devices (2011) and the newest (November 2015) are compared.

- In the Conclusion chapter we sum up the overall results giving an overview of what has been done and providing some post consideration about the work done.
- In the Future works chapter we provide hints for further implementation in order to make ECG-ira really an all in one solution as an ECG mobile application. We also put our consideration about the future of the mobile software with respect to the desktop one, according to the new trend and the fact that the mobile environments is penetrating even more in our daily lives and can really positively change the way patients are connected with the health care providers.

Chapter 2

Electrocardiography overview

This chapter will introduce some basic but fundamental concepts about electrocardiography starting from the heart to the ECG and all issues related to the topic. We will start introducing the heart, its functionality and the entire circulatory system. After that we will describe in details the electrical activity inside the heart and how heart beats are generated. Following there will be a description of the electrocardiogram and the ECG signals. In the last section of this chapter we will discuss about all the noises and interference related to the ECG signal during its acquisition.

2.1 The heart

This chapter's focus is to describe in details the human heart. We will start from the structure to end up describing the heart functionality.

2.1.1 Human heart structure

The human heart is an organ that pumps blood throughout the body via the circulatory system, supplying oxygen and nutrients to the tissues and removing carbon dioxide and other wastes.
This fundamental organ has four chambers: two upper chambers(the atrial) and two lower ones(the ventricles). The right atrium and the right ventricle together make up the "right heart", and the left atrium and left ventricle make up the"left heart". The two sides of the heart are separated by a muscle called the septum.
A double-walled sac called the pericardium, encases the heart, which serves to protect

the heart and anchors it inside the chest. Between the outer layer, the parietal pericardium, and the inner layer, the serous pericardium, runs pericardial fluid, which lubricates the heart during contractions and movements of the lungs and diaphragm. The heart outer wall consists of three layers. The outermost wall layer, or epicardium, is the inner wall of the pericardium. The middle layer, or myocardium, contains the muscle that contracts. The inner layer, or endocardium, is the lining that contacts the blood.

The tricuspid valve and the mitral valve make up the atrioventricular (AV) valves, which connect the atria and the ventricles. The pulmonary semilunar valve separates the right ventricle from the pulmonary artery, and the aortic valve separates the left ventricle from the aorta. The heartstrings, or chordae tendineae, anchor the valves to heart muscles.

The sinoatrial node produces the electrical pulses that drive heart contractions.

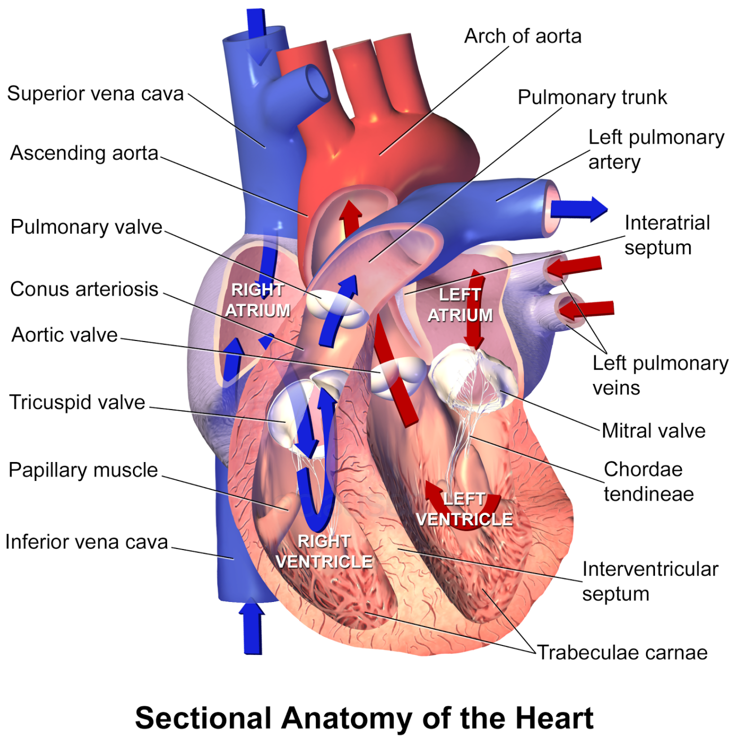

Figure 2.1: The human heart structure.[1]

2.1.2 Human heart function

The heart circulates blood through two pathways: the pulmonary circuit and the systemic circuit.
In the pulmonary circuit, deoxygenated blood leaves the right ventricle of the heart via the pulmonary artery and travels to the lungs, then returns as oxygenated blood to the left atrium of the heart via the pulmonary vein.
In the systemic circuit, oxygenated blood leaves the body via the left ventricle to the aorta, and from there enters the arteries and capillaries where it supplies the body's tissues with oxygen. Deoxygenated blood returns via veins to the venae cavae, re-entering the heart's right atrium.
Of course, the heart is also a muscle, so it needs a fresh supply of oxygen and nutrients too. After the blood leaves the heart through the aortic valve, two sets of arteries bring oxygenated blood to feed the heart muscle. The left main coronary artery, on one side of the aorta, branches into the left anterior descending artery and the left circumflex artery. The right coronary artery branches out on the right side of the aorta.
Blockage of any of these arteries can cause a heart attack, or damage to the muscle of the heart. A heart attack is distinct from cardiac arrest, which is a sudden loss of heart function that usually occurs as a result of electrical disturbances of the heart rhythm. A heart attack can lead to cardiac arrest, but the latter can also be caused by other problems.
The heart contains electrical "pacemaker" cells, which cause it to contract — producing a heartbeat.
Each cell has the ability to be the 'band leader' and have everyone follow. In people with an irregular heartbeat, or atrial fibrillation, every cell tries to be the band leader, which causes them to beat out of sync with one another.
A healthy heart contraction happens in five stages:

1. In the first stage (early diastole), the heart is relaxed.
2. Then the atrium contracts (atrial systole) to push blood into the ventricle.
3. Next, the ventricles start contracting without changing volume.
4. Then the ventricles continue contracting while empty.
5. Finally, the ventricles stop contracting and relax.

Then the cycle repeats.
Valves prevent backflow, keeping the blood flowing in one direction through the heart.

Some interesting data about the human heart are:

- A human heart is roughly the size of a large fist.
- The heart weighs between about 280 to 340 grams in men and 230 to 280 grams in women.
- The heart beats about 100,000 times per day (about 3 billion beats in a lifetime).
- An adult heart beats about 60 to 80 times per minute.
- Newborns' hearts beat faster than adult hearts, about 70 to 190 beats per minute.
- The heart pumps about 6 quarts (5.7 liters) of blood throughout the body.
- The heart is located in the center of the chest, usually pointing slightly left

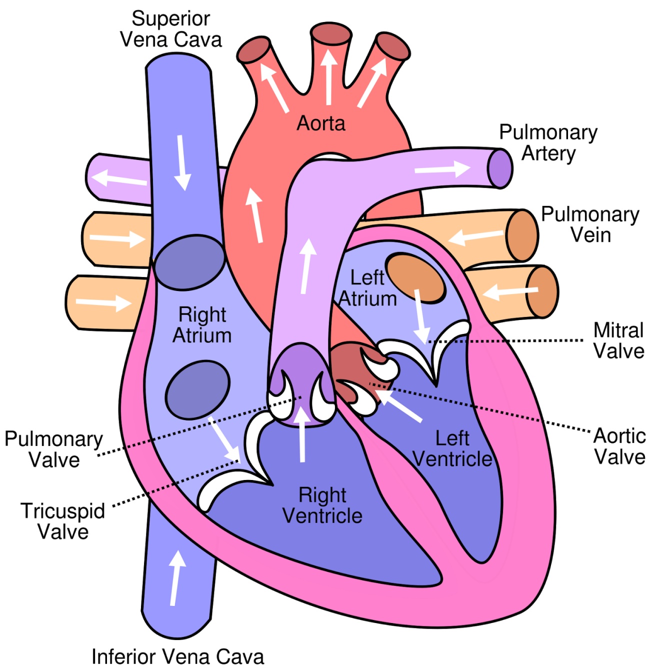

Figure 2.2: The circulatory system with blood flow.

2.2 Heart electrical activity

The heart has a natural pacemaker that regulates the pace or rate of the heart. It sits in the upper portion of the right atrium (RA) and is a collection of specializes electrical cells known as the SINUS or SINOATRIAL (SA) node.
Like the spark-plug of an automobile it generates a number of "sparks" per minute. Each "spark" travels across a specialized electrical pathway and stimulates the muscle wall of the four chambers of the heart to contract (and thus empty) in a certain sequence or pattern. The upper chambers or atria are first stimulated. This is followed by a slight delay to allow the two atria to empty. Finally, the two ventricles are electrically stimulated. In an car, the number of sparks per minute generated by a spark plug is increased when you press the gas pedal or accelerator. This revs up the motor. In case of the heart, adrenaline acts as a gas pedal and causes the sinus node to increase the number of sparks per minute, which in turn increases the heart rate. The release of adrenaline is controlled by the nervous system. The heart normally beats at around 72 times per minute and the sinus node speeds up during exertion, emotional stress, fever, etc., or whenever our body needs an extra boost of blood supply. In contrast, it slows down during rest or under the influence of certain medications. Well trained athletes also tend to have a slower heart beat.

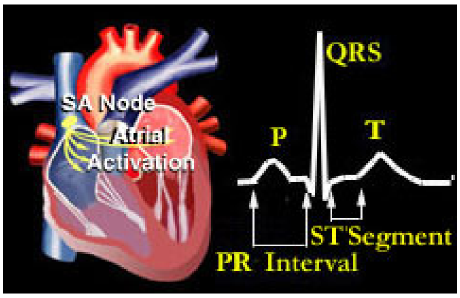

Figure 2.3: The SA node fires and electrical impulses travels through the right and left atrium.

The sequence of electrical activity within the heart is displayed in the diagrams above and occurs as follows:

1. As the SA node fires, each electrical impulse travels through the right and left atrium. This electrical activity causes the two upper chambers of the heart to

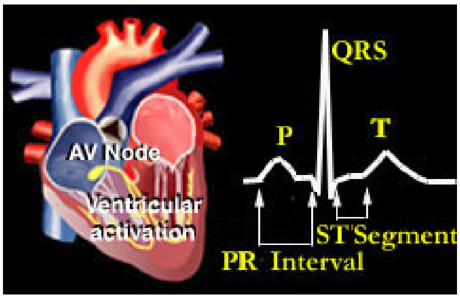

Figure 2.4: The impulse then move to the ventricular area.

contract. This electrical activity and can be recorded from the surface of the body as a "P" wave" on the patient's EKG or ECG (electrocardiogram).

2. The electrical impulse then moves to an area known as the AV (atrio-ventricular) node. This node sits just above the ventricles. Here, the electrical impulse is held up for a brief period. This delay allows the right and left atrium to continue emptying its blood contents into the two ventricles. This delay is recorded as a "PR interval." The AV node thus acts as a "relay station" delaying stimulation of the ventricles long enough to allow the two atria to finish emptying.

3. Following the delay, the electrical impulse travels through both ventricles (via special electrical pathways known as the right and left bundle branches). The electrically stimulated ventricles contract and blood is pumped into the pulmonary artery and aorta. This electrical activity is recorded from the surface of the body as a "QRS complex". The ventricles then recover from this electrical stimulation and generates an "ST segment" and T wave on the ECG.

2.3 Electrocardiogram

An electrocardiogram(abbreviated as ECG or EKG) is a test that measures the electrical activity of the heartbeat. With each beat, an electrical impulse (or wave) travels through the heart. This wave causes the muscle to squeeze and pump blood from the heart. A normal heartbeat on ECG will show the timing of the top and lower chambers.
The right and left atria or upper chambers make the first wave called a "P wave" following a flat line when the electrical impulse goes to the bottom chambers. The right and left bottom chambers or ventricles make the next wave called a "QRS

complex." The final wave or "T wave" represents electrical recovery or return to a resting state for the ventricles.

Each waves in the figure 2.5 is no other than the result of different views or

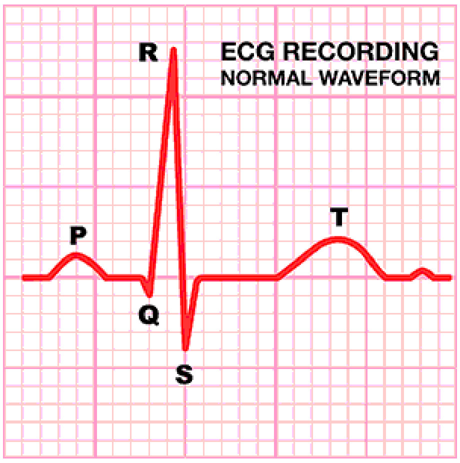

Figure 2.5: An example of a normal ECG waveform.

perspectives of the waveforms generated from the current in the heart.

There are two type of ECGs recordings: the 12-lead ECG and the rhythm strip. Both give valuable information about heart function.

We will focus our attention on the 12-lead ECG. It records information from 12 different views of the heart and provides a complete picture of electrical activity. The limb leads and the chest, or precordial, leads reflect information from the different planes of the heart. Different leads provide different information. The six limb leads I, II, III, augmented vector right (aVR), augmented vector left (aVL), and augmented vector foot (aVF) provide information about the heart's frontal (vertical) plane. Leads I, II, and III require a negative and positive electrode for monitoring, which makes those leads bipolar. The augmented leads record information from one lead and are called unipolar.

The six precordials or V leads V1, V2, V3, V4, V5, and V6 provide information about the heart's horizontal plane. Like the augmented leads, the precordial leads are also unipolar, requiring only a single electrode. The opposing pole of those leads is the center of the heart as calculated by the ECG.

The position of the leads are crucial for a right ECG recordings. It is common to use the so called Einthoven's triangle, a set of positions to set up standard limb leads. The electrodes for leads I, II, III are about equidistant from the heart and form an

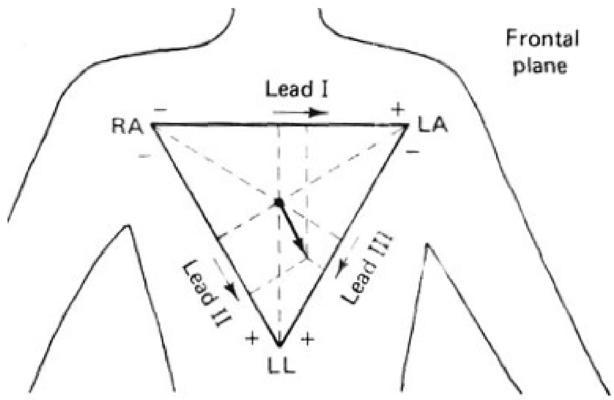

Figure 2.6: The Einthoven's triangle show the right position to place leads over the chest.

equilateral triangle.

2.3.1 Lead I

It provides a view of the heart that shows current moving from right to left. Because the current flows from negative to positive, the positive electrode for this lead is placed on the left arm or on the left side of the chest; the negative electrode is placed on the right arm. Lead I produces a positive deflection on ECG tracings and is helpful in monitoring atrial and hemiblock.

2.3.2 Lead II

Lead II produces a positive deflection. Place the positive electrode on the patient's left leg and the negative electrode on the right arm. For continuous monitoring, place the electrodes on the torso for convenience, with the positive electrode below the lowest palpable rib at the left midclavicular line and the negative electrode below the right clavicle. The current travels down and to the left in this lead. Lead II tends to produce a positive, high voltage deflection, resulting in tall P, R, and T waves. This lead is commonly used for routine monitoring and is useful for detecting sinus node and atrial arrhythmias.

2.3.3 Lead III

Lead III produces a positive deflection. The positive electrode is placed on the left leg; the negative electrode, on the left arm. Along with lead II, this lead is useful for detecting changes associated with an inferior wall myocardial infarction. The axes of the three bipolar limb leads I, II, and III form a triangle around the heart and provide a frontal plane view of the heart.

2.3.4 Augmented leads

Leads aVR, aVL, and aVF are called augmented leads. They measure electrical activity between one limb and a single electrode. Lead aVR provides no specific view of the heart. Lead aVL shows electrical activity coming from the heart's lateral wall. Lead aVF shows electrical activity coming from the heart's inferior wall.

2.3.5 Precordials leads

The six unipolar precordial leads (V1, V2, V3, V4, V5 and V6) are placed in sequence across the chest and provide a view of the heart's horizontal plane.

- Lead V1—The precordial lead V1 electrode is placed on the right side of the sternum at the fourth intercostal rib space. This lead corresponds to the modified chest lead MCL1 and shows the P wave, QRS complex, and ST segment particularly well. It helps to distinguish between right and left ventricular ectopic beats that result from myocardial irritation or other cardiac stimulation outside the normal conduction system. Lead V1 is also useful in monitoring ventricular arrhythmias, ST-segment changes, and bundle-branch blocks.

- Lead V2—Lead V2 is placed at the left of the sternum at the fourth intercostal rib space.

- Lead V3—Lead V3 goes between V2 and V4. Leads V1, V2, and V3 are biphasic, with both positive and negative deflections. Leads V2 and V3 can be used to detect ST-segment elevation.

- Lead V4—Lead V4 is placed at the fifth intercostal space at the midclavicular line and produces a biphasic waveform.

- Lead V5—Lead V5 is placed at the fifth intercostal space at the anterior axillary line. It produces a positive deflection on the ECG and, along with V4, can show changes in the ST segment or T wave.
- Lead V6—Lead V6, the last of the precordial leads, is placed level with V4 at the midaxillary line. This lead produces a positive deflection on the ECG.

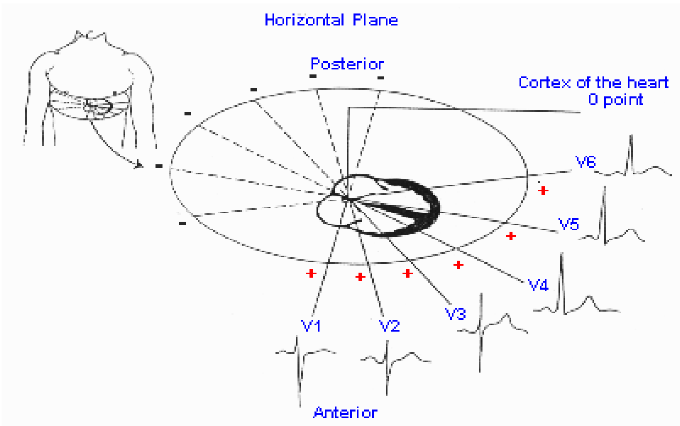

Figure 2.7: Precordial leads and their position related to the heart and the chest horizontal plane.

2.3.6 How to read a ECG record

Waveforms produced by the heart's electrical current are recorded on graphed ECG paper by a stylus. An ECG paper consists of horizontal and vertical lines forming a grid. A piece of ECG paper is called an ECG strip or tracing. The horizontal axis of

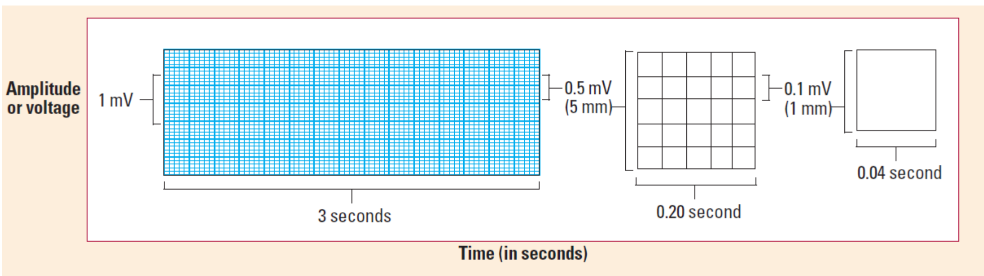

Figure 2.8: A typical ECG paper.

the ECG strip represents time. Each small block equals 0.04 second, and five small blocks form a large block, which equals 0.2 second. This time increment is determined by multiplying 0.04 second (for one small block) by 5, the number of small blocks that compose a large block. Five large blocks equal 1 second (5 x 0.2). When measuring or calculating a patient's heart rate, a 6-second strip consisting of 30 large blocks is usually used. The ECG strip's vertical axis measures amplitude in millimeters (mm) or electrical voltage in millivolts (mV). Each small block represents 1 mm or 0.1 mV; each large block, 5 mm or 0.5 mV. To determine the amplitude of a wave, segment, or interval, count the number of small blocks from the baseline to the highest or lowest point of the wave, segment, or interval.

2.4 Noises and interferences

Obtaining a reliable ECG recording is still an issue. In fact there may occur many problems interfering with the signals. Some of these problems include artifacts from patient movement and poorly placed or poorly functioning equipment.

2.4.1 Artifact

Artifact , also called waveform interference, may be seen with excessive movement (somatic tremor). The baseline of the ECG appears wavy, bumpy, or tremulous. Dry electrodes may also cause this problem to occur due to poor contact.

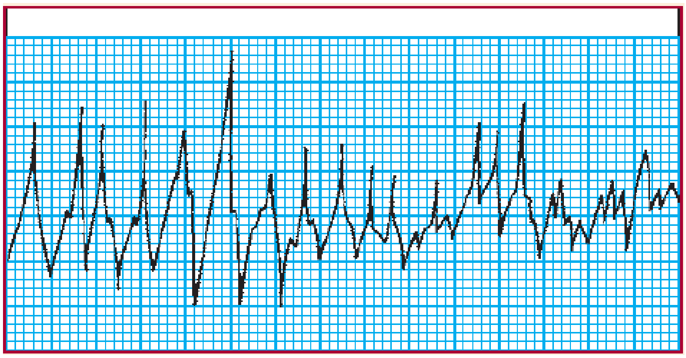

Figure 2.9: ECG waveform interference due to artifact may cause monitoring to fail due to unreadable signals.

2.4.2 Interference

Electrical interference, also called 60-cycle interference, is caused by electrical power leakage. It may occur due to interference from other room equipment or improperly grounded equipment. As a result, the lost current pulses at a rate of 60 cycles per second. This interference appears on the ECGs as a baseline that is thick and unreadable.

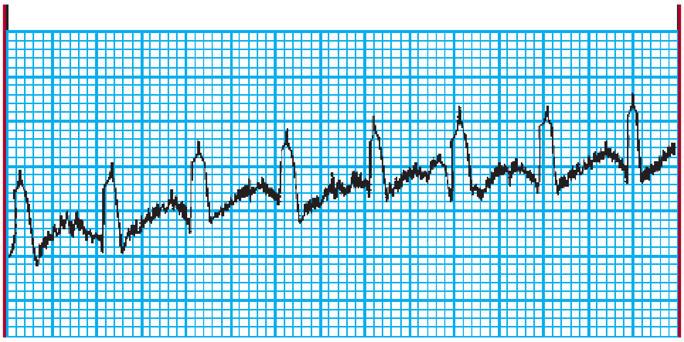

Figure 2.10: Electrical interference causes the baseline to be unstable and the signal is corrupted.

2.4.3 Wandering baseline

A wandering baseline undulates, meaning that all waveforms are present but the baseline is not stationary. It can be caused by movement if the chest wall during respiration, poor electrode placement, or poor electrode contact.

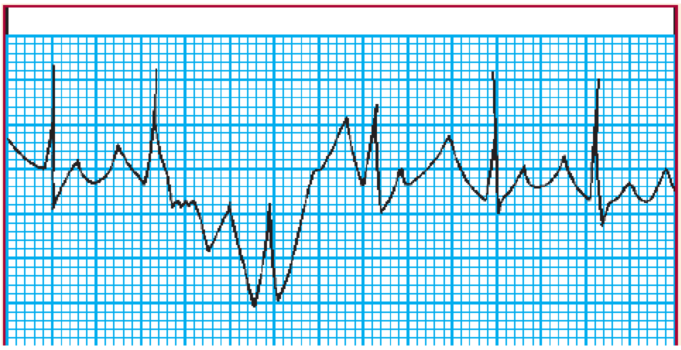

Figure 2.11: An example of baseline wandering due to artifacts.

2.4.4 Faulty equipment

Faulty equipment, such a s broken lead wires and cables, can also cause monitoring problems.

Chapter 3

State of Art

3.1 Device

The personal health care market has changed a lots and recently new products and devices are showing up on the market. We will describe briefly the most relevant and similar products as mobile ECG acquisition devices. We evaluate the following solutions:

- Mortara ELI 10 Mobile
- Philips DigiTrak XT Holter Recorder
- M-Trace (PC) Mobile
- ECG Expert

3.1.1 Mortara ELI 10 Mobile

This device offers an all in one solution for 12 leads ECG acquisition. It is compact and complete as it provides an alphanumeric keyboard and a screen for real time visualization and the possibility to send the record via GPRS/3G channels. For each devices a SIM card is required . The device can also read and interpret the ECG supporting the doctor. Interesting feature is its great interoperability with the main ECG data management systems.

Figure 3.1: Mortara ELI 10 Mobile, ECG acquisition device box.

3.1.2 Philips DigiTrak XT Holter Recorder

This is the smaller acquisition device on the market. Thanks to a proprietary algorithm from Philips it can derive all the 12 ECG leads using only 5 leads. It weighs 62g and the internal battery lasts till 7 days. It also has a small screen showing 1 real time signal at a time.

Figure 3.2: DigiTrack, the ECG visualization.

3.1.3 AliveCor ECG

An innovative solution even though it doesn't offer a complete solution for ECG acquisition and analysis. This small sensor can be attached on the back of your smartphone making it an ECG acquisition device. It can record only one ECG signal (D1), so also the analysis is limited to a few types of arrhythmias . The record length is also limited to 5 minutes.

Figure 3.3: AliveCor device real time acquisition on a tablet.

3.1.4 M-Trace (PC)Mobile

M-Trace PC is an completed 12 leads ECG acquisition device. With the device it comes a mobile application and a desktop pc application used to visualize and analyze the ecg signals. The device is really portable with dimensions 95x64x28mm. The company offers also a more portable device (M-Trace Mobile) to be used by privates at their home. The mobile version cannot acquire a full record but only test records with 6 leads. Its main purpose it to send the test records via GSM/GPRS to the doctor for a faster review.

Figure 3.4: M-Trace PC device for ECG acquisition.

3.1.5 ECG Expert

ECG Expert produced by CSE Medical is a completed solution for ECG acquisition. The device comes with fully supported software for both PC desktop (Windows and Mac) both smartphones (Android, iOS). The device is rechargeable and makes use of a wireless connection via Bluetooth as exchanges data communication with the handheld smartphone or PC software.

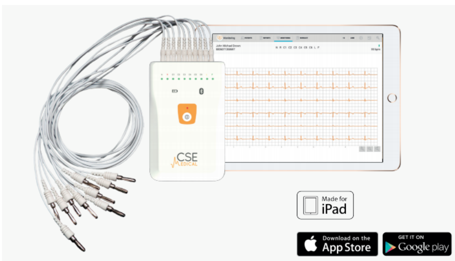

Figure 3.5: M-Trace PC device for ECG acquisition.

3.2 Mobile application

There are already mobile applications on the market store for ECG visualization and analysis supporting different formats. We can distinguish applications that only visualize the signal and the ones that also apply some analysis on the ECG signals. We listed only applications on the Google Play Store, so only Android applications because they are the only comparable with the solution we propose.

3.2.1 Visualization only application

The application on the market able to visualize the ECG signal are:

- *StribogECG*: an Android application based on an open source project under GLP v3 licence. It uses Biosig library to read ECG formats such as scp, xml (hl7), ecg and dgf. The software is only provided as it is and it requires to the user to already have the ecg files stored in those supported formats.

- *AndroidECG*: application on beta release, it was developed by Paco Gonzàles as thesis project during the Master course in Computer Science at the University of Murcia. The application is able to show ECG signals of the following formats: binary, scp, 212. As additional feature it is a basic analysis over the signal to detect QRS complex, P waves, ST segments and T waves. It is also possible to send the ECG record via email.

3.2.2 Visualization and Analysis

The applications on the market that also provide a more detailed analysis over the ECG signal are all bind to a specific proprietary acquisition device. By this way they lack the compatibility and interoperability requirement with other software and ECG formats.

- *M-Trace PC*: the application was developed by *M4Medical*, a Poland company providing medical devices for professionals and private customers. The application only works with the company 12-channel ECG M-Trace PC register device. The main features are the real-time monitoring interface, a patients' database management system and the possibility to share the record.

- *ECG Expert*: developed by *CSE Medical* the application works only connected to an ECG-Expert acquisition device. The main features are the real-time view of the acquisition, the analysis of the record providing information about QRS complex and heart rate, the possibility to manage patient information bind to the record and a heartbeat Normal/Abnormal classifier.

One last mobile application, which is not strictly related to ECG signal visualization and analysis but it worth to be mentioned, is the *ECG Interpretation*. This application instead provides enough detailed information about how to read and interpret the

ECG signals through 32 small lectures. All the lectures provide a picture and a short description and explanation.

Chapter 4

Problems

By identifying the requirements, we could then be able to highlight the related problems that we had to face in order to fulfill all of them. We will describe the related requirement as source of each faced problem.

4.1 Mobile platform fragmentation

Considering the requirement of a wide platform compatibility, we obviously need to face a really big problem in the mobile application world: the platform fragmentation. Starting from the first smartphone release on 2007, the iPhone from Apple, the sale of such devices keeps increasing each year. Between 2007 and 2008 sales proceeded upwards reaching the same sale rate of their computing parent, the PC. On 2009 the market signed an important inflection point, representing the beginning of an inexorable vertical rise. Although PCs were still the only ones to offer some types of functionality due to their longer replacement cycle, they were sold with a ratio of $1 : 2$, compared to smartphones, over a 5 year period. This new market' growth leads to an obvious seeking of various participants, some by choice and some by necessity, in order to extract value. Android has been the prime beneficiary, having been announced on 2007 and having gone on to account for well over half of smartphone sales worldwide. Apple, meanwhile, has maintained a steady ship, leveraging its skill in product design and user experience with a finely honed marketing machine, attracting a customer that rarely defects.[3] Fast-forwarding to 2016, if we consider the global market share held by the leading smartphone operating systems, at first position we have Android with a share of 80.7%, followed by iOS with a 17.7%. Minor percentages are represented

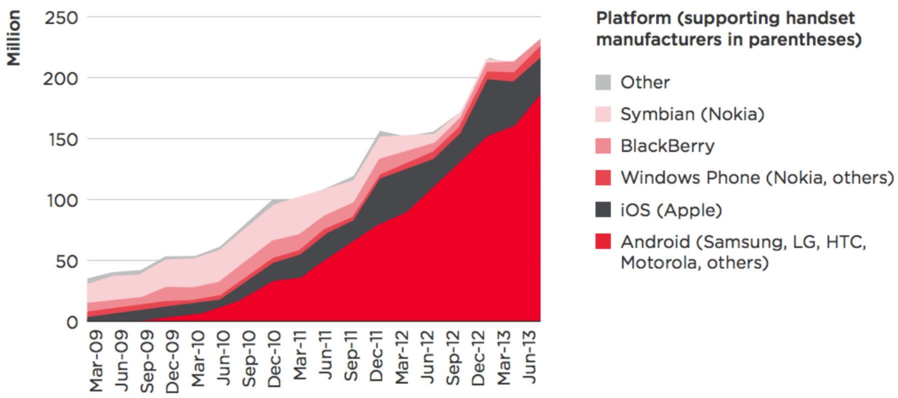

Figure 4.1: Mobile platform share evolution (smartphone sales), 2009–13.

by Windows Phone (1.1%), RIM (0.2%) and others (0.2%).[4]

4.2 Native vs Cross-Platform

As mentioned earlier, one of the main challenges when moving to a mobile solution is the software development within a technology landscape that is highly fragmented and rapidly evolving. Mobile apps require a fair amount of customization to run on diverse platforms and a constant update due to the steady stream of new hardware, OS versions and browsers. Even a single platform (Android, Windows, Blackberry, and to a lesser extent Apple) has numerous flavors that require some degree of customization. There are also other factors such as the overlay software from different manufacturers that can affect behavior of an app on a particular device.

In response, the mobile industry has spawned a rapidly growing ecosystem of cross-platform and cross-device frameworks, source code analyzers, libraries of reusable components, and other tools designed to accelerate and simplify multi-platform development. New tools are constantly emerging, with new functionality, different capabilities, strengths and weaknesses.

Developer's preferences change and evolve, particularly as new tools and capabilities become available. However, the basic goals are the same: to code less and accomplish more, to reuse and recycle across multiple platforms as much as possible, and consider developing from scratch as the last resort. In addition, any tool or framework should be able to work with current and future evolving offers, and not to be locked because of a particular platform or technology.[5]

4.2.1 Native

Native app development involves developing software specifically designed for a specific platform, hardware, processor and its set of instructions. Typical programming language are Java, Object C, Swift, C# and many other.
Native apps' major advantage over cross-platform apps is the ability to leverage device-specific hardware and software. This means that native apps can take advantage of the latest technology and API available on the mobile devices and it can well interface with other platform apps. Other advantages are a predictable increase on performance, streamlined support, native UI, native API and coherent library updates. However, the mobile platform's fragmentation makes the task of keeping up with the pace of emerging technology onerous and costly, having to develop different software for each of the different platforms (Android, iOS, Windows Phone, Symbian).
Going further on a more technical analysis, native applications are represented by executable binary files that will be installed into devices without the need for other abstraction layering to the operating system. They are able to call built in functionalities such as calendar, notifications, the dialer, email provider and others services and functionalities provided natively by the OS. Despite the fact that native applications development requires platform specific skill and expertise, this strategy delivers a higher quality user experience than other mobile application development methods (cross-platform or hybrid approach). Native apps are also best distributed through an app store.[6]

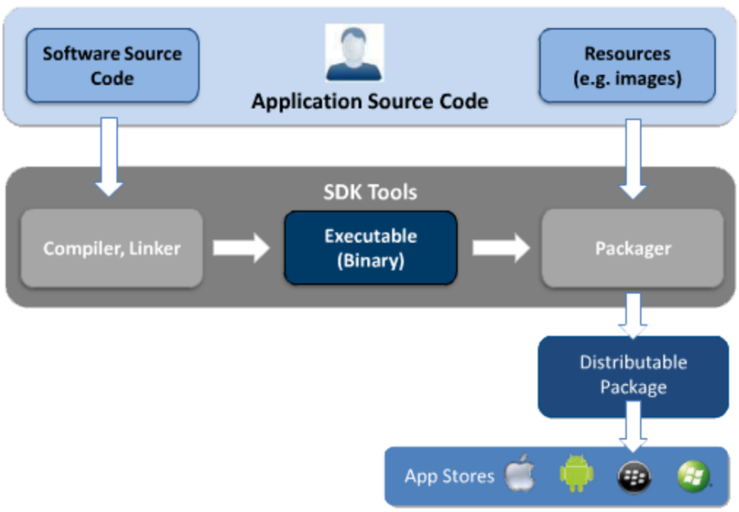

Figure 4.2: Native app development process.

4.2.2 Cross-Platform

Cross platform development produces one code base to maintain and write targeting multiple devices and platforms. It promises lower time of development and costs. The main categories of this group are web, hybrid, interpreted and generated apps. None of the previous is neither prevalent nor the best solution to the problem of developing cross-platform mobile applications. The main benefits of cross-platform development

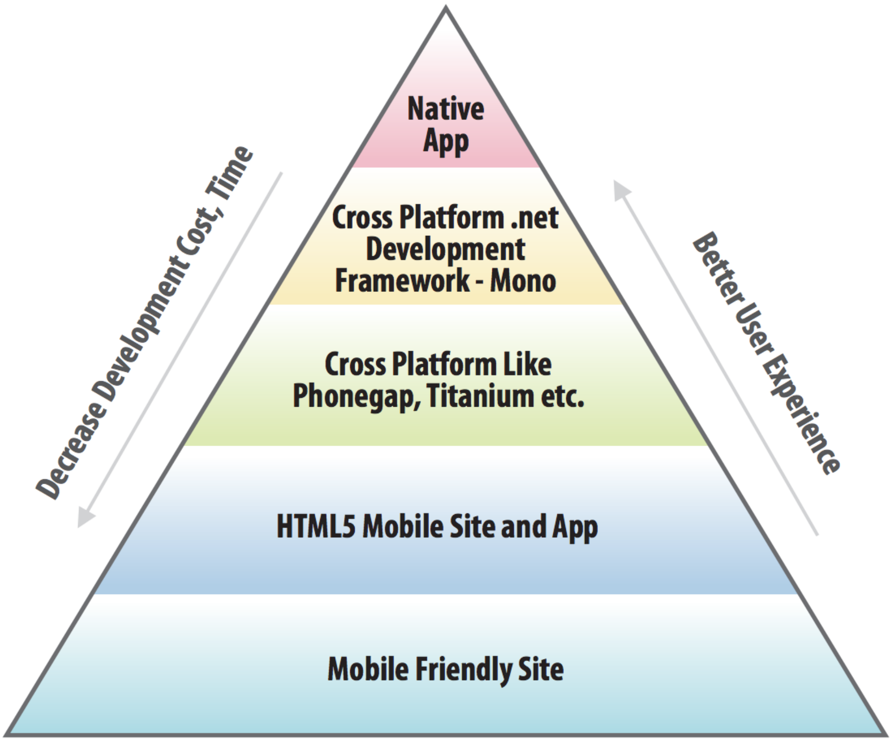

Figure 4.3: Native vs Cross-Platform cost and time factors.[2]

are:

- Reduction of required skills to develop applications due to the use of common programming languages;
- Reduction of coding work, because the source code is written once and it is compiled for each supported OS;
- Reduction of development time and long term maintenance costs;
- Decrement of API knowledge, because with these tools is not needed to know the API's of each OS, but only the API's provided by the selected tool.[7]

4.3 Mobile hardware limitations

As this project started from a previously developed desktop application, we needed to take into account all the limitation of mobile devices hardware. Despite the trend of mobile hardware is a constant increasing in computational power and memory availability, we cannot compare it with the one available nowadays in PC architectures, as the architectures on this two platforms are totally different: most of all pc are based on x86 architectures, whereas mobiles rely on ARM architectures. Furthermore, we could not commit the error of targeting only recent devices as they represent only a small percentage of all devices in the market, and it would have been in contrast to our main goal, which is a wide device compatibility. We will discuss briefly about memory and computational differences in these type of architecture in the next paragraphs.

4.3.1 Memory limitations

The first point to consider is the device memory limitation. In the previous desktop application not so much effort was spent to reduce memory allocation: all the ECG record samples were allocated in memory both during acquisition and record opening. This approach could result convenient considering its low implementation effort, but it could be source of lots of problem when moving to a mobile device, where not only the physical memory are often small, but also the memory reserved to an application is limited (Figure 6.4), both due to the coexistent apps running in the system and the power management of the mobile OSs. So we needed to find a good approach in order to manage these problems and not to face with memory leakages.

4.3.2 Performance limitations

Talking about cpu computational power there is a huge gap between the two architectures.. Not considering the evident difference for what regarding the space availability for the CPU package, the main difference is that ARM architectures are focused on reducing the power consumption, a crucial characteristic in mobile devices. A technical report analyzed the execution time of a benchmark using a cross-platform version of WebKit showed that the tested ARM A9 architecture had a ratio of 5.8 (normalized time) compared to the tested x86 architecture.[8]

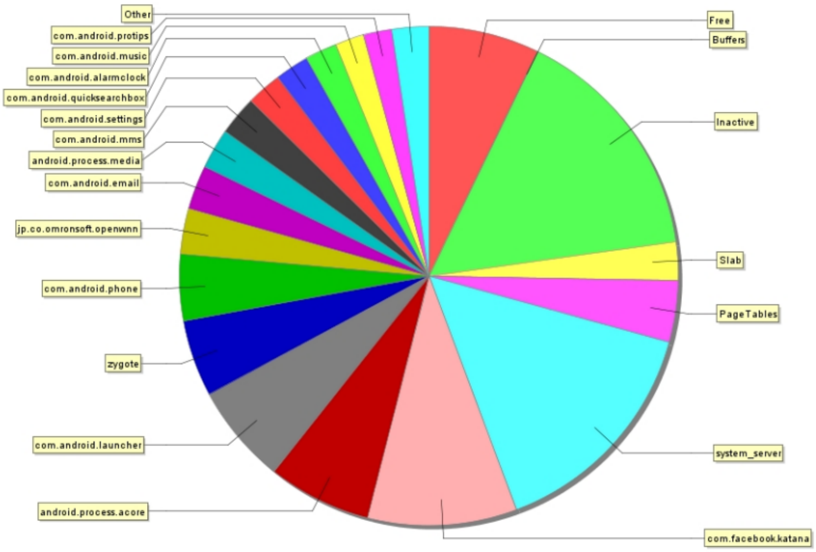

Figure 4.4: Memory reserved to an app in Android.

4.4 ECG baseline wander

For a right interpretation and identification of physiological and pathological phenomena, a low error is required in the ECG signal. But often ECG recordings are distorted by two main artifacts:

- high-frequency noise caused by electromyogram induced noise, power line interferences, or mechanical forces acting on the electrodes;
- baseline wander (BW) that may be due to respiration or the motion of the patients or an instrument fault (Figure 6.5).

These artifacts strongly limit the utility, readability and interpretation of a recorded ECGs. In ECG enhancement, the goal is to separate the valid ECG from the undesired artifacts so that we can extract a signal that allows an easy visual interpretation.[9] The first class of artifact is mostly solved within the acquisition device at hardware low-level though filters and a proper settings. In this project we will deal with the second class of artifact which can be managed at software level.

4.4.1 State of Art

Two methods, in recent years have often been applied to remove BW:

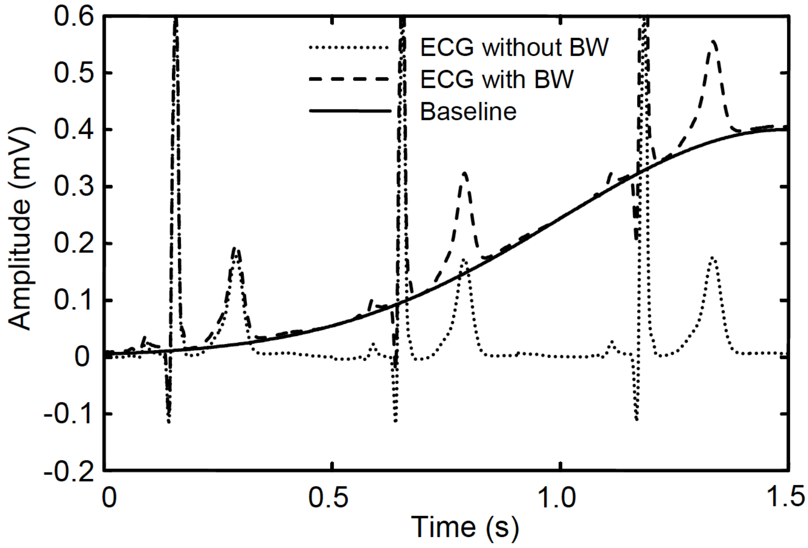

Figure 4.5: The baseline wander artifact in the ECG signal.

- Polynomial fitting: in order to assess the baseline, it uses a polynomial interpolation. The baseline is fit from some fiducial points that are determined from P-R intervals, whereas these fiducial points are difficult to accurately locate before noise is removed from the ECG signal. As result this approach is ineffective if the ECG signal is contaminated by noise.[10]

- High-pass filtering: to implement this type of filtering, usually a moving average filter[11] and wavelet translation[12]. This approach however would unavoidably introduce distortions in various parts of the ECG signal, especially in the ST segment due to the spectra of the ST segment that overlaps the spectra of BW.

Simple Moving Average Filter

This type of filtering is defined as

$$y(n) = \frac{1}{2N+1} \sum_{i=-N}^{N} x(n+i) \tag{4.1}$$

where $x(n)$ and $y(n)$ are input signal and output signal of the moving average respectively, and N specifies the observation window length equal to $2N+1$. So the baseline can be estimated as

$$z(n) = x(n) - y(n) \tag{4.2}$$

where $z(n)$ is the output signal of the high-pass filter.

Distortion using Simple Moving Average Filtering

Obviously the baseline values estimated from the P-R segment (between 0.3 s and 0.6 s) are very close to real baseline values, while the baseline values estimated from segments including QRS complex and T wave are far away from the real baseline. Therefore, if an observation window covers some sample points with extreme amplitudes, an ECG signal would be distorted.

CPU intensive operation

Many methods are known in the literature that perform better and reduce the error in the ECG signal due to the filtering, like wavelet package translation filter[13], or the statistical weighted moving average filter[14]. Defined the normalized root mean square error ($NRMSE$) and maximum error (ME) as

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{L}(ecg_{in}(i) - ecg_{out}(i))^2}{\sum_{i=1}^{L} ecg_{in}(i)}} \tag{4.3}$$

$$ME = \max_{i=1,2,\ldots,L} |ecg_{in}(i) - ecg_{out}(i)| \tag{4.4}$$

The figure 4.6 shows a comparison between the methods. Of course the computational complexity these advanced methods is really high. Considering that this type of filtering is supposed to be used during a real-time acquisition in our project, they are obviously prohibitive.

4.5 Signal visualization

The problem of an efficient ECG signal visualization shows up when the application has to plot samples of an acquisition device with a rate of 500Hz. Because of this the app has to be able to draw $500 - 1$ lines (connecting two samples) for each mapped second in the ECG paper grid. Taking into account the standard size of a second

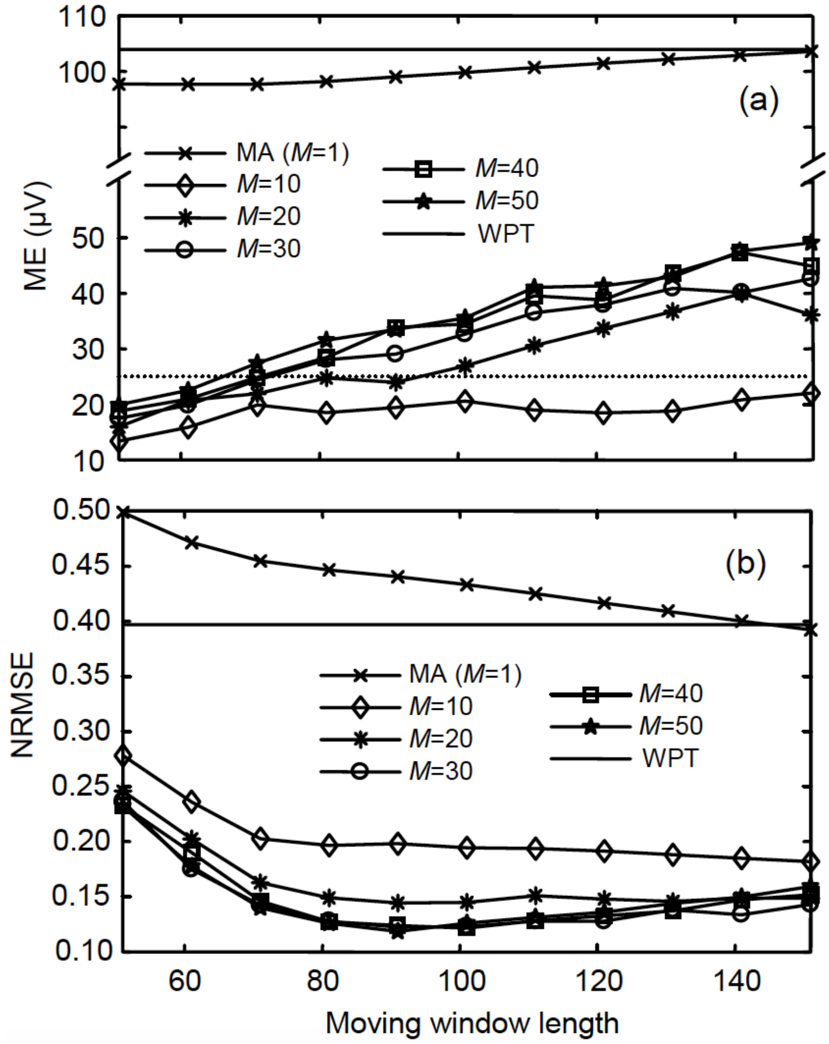

Figure 4.6: Relation between distortion and moving window length for wavelet package translation (WPT), traditionally used MA, and our proposed high-pass filter based on a statistical weighted moving average (SMA).
(a) Maximum error (ME) vs. moving window length;
(b) Normalized root mean square error (NRMSE) vs. moving window length. M is the number of sub-bounds. SMA is the same as MA when M=1.

in the standard ECG paper of 5mm, and the fact that the visualization size has to respect this measure, if we consider a device screen of 4.6 inch in portrait, we have around 11 seconds of samples to visualize. Hence we have $(500 - 1) * 11 = 5489$ lines to plot. If we are supposed to plot ideally all the ECG derivation (12), the number of total lines become $5489 * 12 = 65868$. Now, this is the number of lines we need to plot in order to cover the total visible window screen space. If we want to

have a good display smoothness we must guarantee at least 30FPS (frame rate per seconds), ideally 60 frame/s (FPS). Assuming a minimum of 30 FPS we have a total of $65868 * 30 = 1976040$.
These numbers gives us an idea of the computational effort that is spent only only to plot the samples.

Acknowledgement

Desidero innanzitutto ringraziare...

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