A WIRELESS APPLICATION THAT MONITORS ECG SIGNALS ON-LINE: ARCHITECTURE AND PERFORMANCE[1]

Jimena Rodríguez, Lacramioara Dranca, Alfredo Goñi and Arantza Illarramendi
University of the Basque Country (UPV/EHU).LSI Department. Donostia-San Sebastián. Spain

Keywords: Wireless Application, Mobile Computing, Wireless Network, ECG Monitoring System

Abstract: In this paper, we present an innovating on-line monitoring system that has been developed by applying new advances in biosensors, mobile devices and wireless technologies. The aim of the system is to monitor people that suffer from heart arrhythmias without having to be hospitalized; and therefore, living a normal life while feeling safe at the same time. On the one hand, the architecture of the system is presented; and, on the other hand, some performance results and implementation details are explained showing how the previous solution can be effectively implemented and deployed into a system that makes use of PDAs, and wireless communications: Bluetooth and GPRS. Moreover, special attention is paid to two aspects: cost of the wireless communications and notification latency for the detected serious heart anomalies.

1 INTRODUCTION

Innovations in the fields of PDAs, wireless communications and vital parameter sensors enable the development of revolutionary medical monitoring systems, which strikingly improve the lifestyle of patients, offering them security even outside the hospital.

In this context we are developing a system that takes advantage of the latest advances in the technology in order to monitor on-line, people that suffer from heart arrhythmias. The system allows an anywhere and at any time monitoring and provides to its users the adequate medical assistance. So, the patient could have a normal life in his/her habitual environment without being constrained to a hospital room. The patient's tool, which replaces the traditional monitor (Holter) and supports Bluetooth technology, is reflected in a standard PDA that is a small, handheld computer that captures, processes, detects, analyzes and notifies possible abnormalities to a medical unit through the wireless network (GPRS) from anywhere and at any time. Moreover, the Bluetooth communication makes this tool even more comfortable for the user, replacing the cables of the sensors that pick up the cardiological signals.

Concerning related works, on the one hand, there are several commercial tools designed to monitor heart patients outside the hospital; from the traditional Holter (Despopoulos, 1994) that simply records heart signals named ECG (electrocardiogram), for 24 or 48 hours, which are later analyzed in the hospital, until the modern cellular phones e.g Vitaphone (Daja, 2001) that, in case of an emergency, can record the signals through the metal electrodes situated on its back and transmit them to the cardiac monitor center situated in the hospital. There are other commercial monitoring systems that use PDAs to store the ECG signals, e.g. Ventracor (Ventracor, 2003), Cardio Control (Cardio Control, 2003). For these systems additional features like GSM/GPRS transmission to an analyzing unit are also being developed.

On the other hand, in the research monitoring area, stand out several research projects like: @Home (Sachpazidis, 2002), TeleMediCare (Dimitri, 2003), or PhMon (Kunze, 2002), whose aims are to build platforms for real time remote monitoring.

All these systems are continuously sending ECGs to a medical center through a wireless communication network, where the signals are

[1]This work was mainly supported by the University of the Basque Country and the Diputación Foral de Gipuzkoa (co-supported by the European Social Fund)

Rodríguez J., Dranca L., Goñi A. and Illarramendi A. (2004).
A WIRELESS APPLICATION THAT MONITORS ECG SIGNALS ON-LINE: ARCHITECTURE AND PERFORMANCE.
In *Proceedings of the Sixth International Conference on Enterprise Information Systems*, pages 138-145
DOI: 10.5220/0002640101380145

analyzed. In spite of the advantages these kinds of systems provide in relation to holters, they still present main problems related to the fact that the analysis is not performed in the place where the signal is acquired. Therefore, there is a *loss of efficiency* in the use of the wireless network because normal ECGs are also sent (and wireless communications imply a high cost); and, if the wireless network is not available at some moment (e.g. in a tunnel, in an elevator, etc.), there might be a loss of ECG signal with the corresponding risk of *not detecting some anomalies*.

Our proposal, the MOLEC system, is a PDA-based monitoring system that records user ECG signals and *locally* analyzes them in order to find arrhythmias. In case of detecting a high risk situation for the user, it sends an alarm with the corresponding ECG signal through the wireless network (GPRS) to a health center for further analysis and medical assistance.

The advantages of this approach are that provides 1) *local analysis:* even if wireless communication with the health center were unavailable, the signal could be analyzed locally at the PDA; 2) *low cost communication* since not the entire signal is sent; 3) *fast medical response* in risk situations for the user; 4) *accessibility*: data recorded in the system can always be queried whether locally or remotely; 5) *distributed computation:* the local analysis in each PDA implies a serious decrease of computational costs in the health center; 6) *openness*: it can be easy integrated in hospitals that manage clinical data through the XML and HL7 standard (HL7, 2003), a representation of clinical documents; 7) *adaptability*: possibility of working with different kinds of ECG sensors; 8) *simplicity*: making technical issues transparent to the users from the point of view of software and hardware components.

The goals of this paper are to present the global architecture of MOLEC, and more specifically the software modules needed in the PDA (in section 2); and to introduce some implementation details (in section 3) and performance results (in section 4), focusing on two important aspects: minimizing the cost of the wireless communications and obtaining a reasonable notification latency for the detection and notification of serious heart anomalies. Finally, in section 5, we present the conclusions.

2 GLOBAL ARCHITECTURE

Three main components form the global architecture of MOLEC (see figure 1, from left to right): 1) The ***ECG Sensors*** that pick up the electric impulses of the heart. These sensors are the "intelligent" chips that communicate with the PDA through the bluetooth protocol. 2) The ***PDA-Holter*** that acquires the data signal in a PDA, records them, detects abnormalities and notifies them immediately in case they are considered serious. 3) The ***Molec Hospital*** receives the user alarm signals that are shown to the medical personal so that they can react promptly.

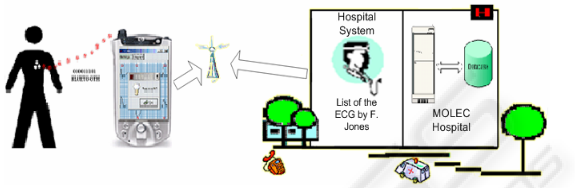

Figure 1: Architecture

2.1 ECG Sensors

The ECG sensors are carried by the user in order to register heart signals and send them to the PDA through the bluetooth protocol (Bluetooth, 2003). Bluetooth is a new standard for very low cost, short-range wireless communication. It enables different types of equipment to communicate wireless with each other and has been thought of as a cable replacement becoming the fastest growing communication standard ever.

Hence we consider that this technology has a promising future for the area of the ECG sensors and we developed the MOLEC project for the integration with bluetooth ECG sensors.

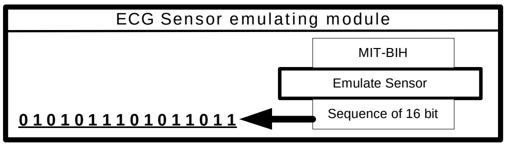

Figure 2: ECG sensor emulating module

Unfortunately, nowadays ECG sensor providers only sell their products with proprietary electrocardio analyzer software. That is why, in our case, the PDA communicates through bluetooth with an ECG sensor emulator placed in a computer device. The ECG signals are taken from a recognized freely distributed database, namely MIT-BIH Arrhythmia database (MIT-BIH, 2003), and sent in real-time as bit sequences to the PDA through the wireless network (see figure 2).

On the other hand, in the PDA-Holter, the Acquisition module receives the bit chains and translates them into a standard format that the whole system understands.

2.2 Molec Hospital

The other system that interacts with the PDA-Holter is the MOLEC Hospital whose main function is to customize the PDA-Holter for each user and to receive users' possible abnormalities. It maintains a large database with all the users registered, their historical and their progress. This could be very useful for the specialists when diagnosing or taking fast decisions in alarm cases.

Furthermore, MOLEC Hospital provides web services that allow querying user data stored in the PDA.

Those web services provide the same functionality that holters have associated in the specialized literature (Farreras, 2001) by a set of reports, which enables physicians to analyze the data easily and quickly and shows information about: 1) automatic arrhythmia detection and identification; 2) analysis of ST segments evolution; 3) ECG parameters. Therefore the data in the database can be queried, locally or remotely, to know different aspects that can be related to the anomalous situations.

In addition, the hospitals can easily incorporate the MOLEC Hospital system into their administration system since it does not interfere with existing applications.

2.3 PDA-Holter

The ***PDA-Holter*** is the user tool of MOLEC. It is responsible for acquiring the ECG data signal, recording it, detecting abnormalities and notifying them immediately in case they are considered serious. The PDA-Holter is formed by several modules that are explained in the next subsections.

ECG Signal Acquisition

The ECG signal acquisition module receives the digital signal and converts it into a format understandable by the whole system. It manages the Bluetooth communication among the ECG sensors and the PDA. Moreover it has to build signal packages (the “source packages”) with a defined size from the bit chains received from the ECG sensors. In section 4, we present the experimental results that have leaded us to define the correct size of these packages.

Data Preprocessing Module

This module obtains the ECG signal in form of source packages and detects the typical part of the beat. An ECG signal consists of several beats that succeeds with a frequency between 60 and 100 per minute. A normal beat contains a P wave, a QRS complex and one or two T waves. For the arrhythmia detection it is significant the identification of the presence or absence of these waves, the points where start, end and the peaks of them. We call these points ‘wave events’.

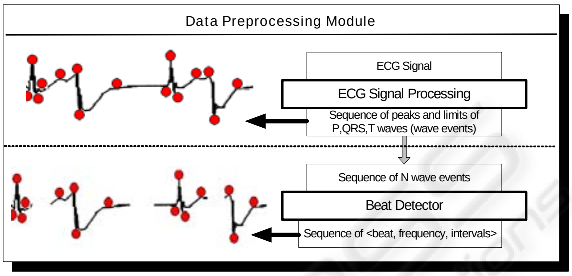

Figure 3: Data preprocessing module

The goal of the data processing module is to detect each beat from the original signal and the points that characterize it. This work is even more difficult if the signal has a high level of noise.

The task is realized in two steps (see Figure 3): Firstly, the ECG signal is processed in order to detect wave events (ECG Signal Processing). For the implementation of the ECG Signal Processing we have used, although slightly changed, a Fortran implementation (Jané, 1997) of an on-line detection algorithm developed by Pan & Tompkins (Pan, 1985) and provided by the recognized PhysioNet (PhysioNet, 1997). This tool was not specifically designed to be run in small computers like PDAs and usually has been used to process long ECG signals. However, we have been able to run it successfully in the PDA using as input small ECG signals (those corresponding to the “source packages” previously mentioned). Only minor changes related to memory management have been made in the “open source” of Ecgpuwave with the goal of increasing the processing speed.

Secondly, the sequence of wave events is transformed into a sequence of beats, it is computed the length of the relevant intervals and segments determined by two wave events (Beat Detector).

Decision Support Module

Once the beats with the corresponding wave events have been detected, the system can start the arrhythmia detection, task which is realized by the Decision Support Module (see Figure 4). Two main steps take place during this analysis: identification of the beat types and classification of the arrhythmias.

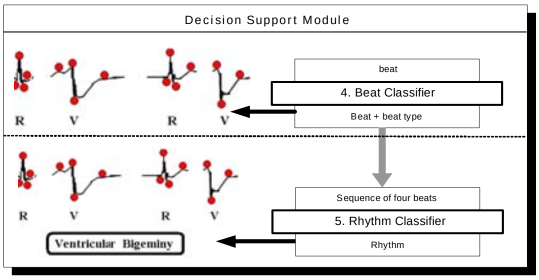

Figure 4: Decision Support Module

In order to *classify the beat* we have tested seventeen methods (Rodriguez, 2003) from the machine learning area and we have chosen the most appropriate one for this kind of data: the decision tree methods (Le Blanc, 1986) that approach discrete-valued target functions. The learned functions are represented by decision trees, but they can also be re-represented as a set of if-then rules to improve human readability. Those rules have been extracted, codified in a programming language and tested. The validation of the rules previously generated took place using the hold-out validation.

In order to *classify the rhythms*, we used a combination of rules: Cardiologic and Inferring rules. The Cardiologic rules were obtained through the translation of the arrhythmia descriptions found in the specialized cardiologic literature (Farreras, 2001) and in parallel, we obtained the Inferring rules by using techniques based on decision trees. Finally we combined them and chose the best rules to detect each rhythm. More details about the decision support module can be found in (Rodriguez, 2003).

Data Manager Module

The main goal of this module is to efficiently manage the restricted memory resources available in the PDA, at least when compared to the great capacity of ECG sensors to generate data.

It has knowledge about all the signals that are being acquired and the stage of its processing. For each packet, once the classification of the beats and rhythm is done, the Data Manager decides how to store each beat: in a regular file or in a database. Normal ECGs are stored in compress files and the anomalous ones are stored at the PDA database. More details about the data manager module can be found in (Rodriguez DOA, 2003).

Alarm Manager Module

This module receives the current heart rhythm and associated parameters and decides whether to generate an alarm. Not all the arrhythmias should be sent in real time to cardiologists so that they can confirm them and/or make their decisions: only those considered very dangerous by them.

With the help of some cardiologists, we have considered two groups, one for high-risk arrhythmias, that is, arrhythmias that should be notified to the hospital when they were detected by the system and the other one for the moderate-risk arrhythmias and normal rhythms that are stored but not immediately notified.

Moreover, we have defined a personalized alarm notification policy that allows deciding if an alarm is sent or not depending on the user parameters. For example: if the patient X presents a short ventricular tachycardia (a high-risk arrhythmia), that alarm would not be notified if the physician had previously defined that, for patient X, only tachycardias longer that thirty seconds should be notified. It has to be noticed that an on-line monitoring system like this would be useless if the cardiologists were bothered with not really relevant arrhythmias very often.

Sender Module

This module is in charge of the communication control between the PDA and the hospital. Hence, it establish and maintain the connection in order to send the alarm messages with the corresponding ECG signal fragments and to answer to the report or query solicitations that the hospital could make. A standard is used to transmit medical data: HL7 (HL7, 2003) that is contained into the XML message. An HL7 representation of clinical documents is called Clinical Document Architecture (CDA). The CDA is a document that specifies the structure and semantics of a clinical document. It can include text, image, sounds and other multimedia content. When the message is received by the hospital, the physician reads the report and confirms the result obtained by MOLEC. Notice that there are tools that can show the data represented in HL7 messages to physicians.

Interface Module

The interface module is responsible for data visualization and measurements display. The figure 5 shows a picture of the PDA-Holter. It provides a friendly interface that draws the ECG signal as soon as the current beat and rhythm types are obtained on-line by the Decision Support Module.

3 IMPLEMENTATION DETAILS

The platform used for the implementation of the PDA-Holter part of MOLEC has been the next PDA:

Figure 5: ECG visualization in MOLEC

an iPaq 3970 which is a powerful device with a 400Mhz XScale processor, 64MB SDRAM and 48 MB Flash memory. Besides, it has a Linux support, the Familiar Linux distribution (Handhelds 2003), converting it in a complete embedded Linux system.

In figure 6, it can be observed that Linux has been the chosen operating system. The external layer of the figure shows the MOLEC modules that have been explained in the previous section and in the middle layer they can be seen the programming languages used for the implementation of them.

We chiefly have used Java because it is: 1) an object oriented language, 2) platform independent, 3) type safe; it provides 4) automatic memory management, 5) built in threads, 6) synchronized primitives and 7) exception handling, which makes it proper for the development of a critical time system like MOLEC is. Although many people agree that the Java performance is not as good as the one offered by other programming languages, this happens only with interpreted Java. In our prototype, we have compiled the Java source code with the GNU compiler for Java (GNU, 2003), what increased dramatically the processing performance.

For the signal preprocessing part, as this task supposes several mathematical calculus, we chose the Fortran and C languages.

For the implementation of the interface module, we have used the SWT libraries (Eclipse, 2003) because it has been possible to integrate them into our PDA platform (Xscale processor and Linux operating system), and to compile them with the GNU compiler. Moreover, they have provided a very acceptable processing performance (faster than graphical libraries that usually come with Java distributions like AWT and Swing).

For the wireless communications, two technologies have been used: the Bluetooth technology and the General Packet Radio Server (GPRS). Bluetooth is a digital connection wireless standard that can transmit data up to a rate of 1 Mbps; and GPRS is a wireless network that allows sending and receiving data packages and its bandwidth is up to 56 Kbps. In section 2.1, we explain the difficulty to obtain the ECG sensors, so for the tests we have performed, the PDA communicates through Bluetooth with an ECG sensor emulator placed in a computer device. The ECG signals are taken from a recognized freely distributed database, namely MIT-BIH Arrhythmia database (MIT-BIH, 2003).

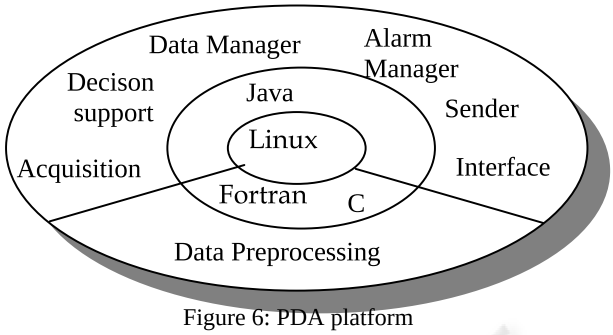

Figure 6: PDA platform

4 PERFORMANCE RESULTS

The main goal of our system is to monitor on-line the ECG signal from people suffering from heart arrhythmias. The technology proposed for the system, PDAs and wireless communications, imposes some restrictions that affect the design of MOLEC.

On the one hand, working with wireless communication technology is more expensive than using wired communication technology. Therefore, it is interesting to pay special attention to try to minimize the cost of the wireless communications and, at the same time, not to delay the notification of serious heart anomalies to the hospital.

On the other hand, it is known that the most powerful current PDAs, even with the latest technological advances, are environments with limited computing resources if compared to PCs.

Moreover, the processing tasks that a monitoring system implies require a high computation cost: the signal processing that obtains the sequence of beats, the classification process of those beats and the corresponding rhythms, and the visualization of the ECG signal. Note that the ECG sensors generate data very quickly. In our case, the data stored correspond to a signal with a frequency of 360 samples per second what is equivalent to 21,600 samples/minute.

Hence, we focus on efficiency in order to prove that a local processing of the ECG signal in a PDA would not introduce too much latency in detection of eventual alarms, compared with a system where the processing is made remotely.

The proposed architecture in section 3 is a functional solution for an ECG monitoring. However, it is also necessary a proper configuration of the processing threads of the system in order to obtain a system stable in time.

Therefore, it is essential to answer to the next question: how often does the analysis process have to be executed?, or, in other words, which is the proper size of the “source package” provided by the “ECG Signal Acquisition Module” that starts the processing in the PDA?

In this section, we are going to present the experiments that we have made with the goals of: calculating the rate of the processing cycle that the system can tolerate in order to not get overloaded, thus the smallest rhythm detection delay (finding the optimal processing rate); and of estimating the latency of the alarm notification and the communication costs with a medical monitoring center.

The test results are compared with the results obtained for the same parameters in a PC.

4.1 The optimal processing rate

Each time the ECG Signal Acquisition receives ECG samples, the system must analyze them in order to find arrhythmias, performing in this way an *entire processing cycle*. The question we try to answer here is how frequently we should perform this processing, in other words, which is the processing rate for the system.

On the one hand, as we have mentioned in section 3, in order to identify arrhythmias, first we have to detect the beats from the ECG signal. The typical occurrence of the beats, in one minute, is between 60 and 100, therefore, the entire processing cycle (that means also the size of the ECG signal package analyzed) should not be less than one second since the probability to find a beat in such a short time interval is really tiny and besides, the algorithm of detecting the wave events is more accurate with longer signals.

On the other hand, the smaller the cycle duration is the faster the alarm detection could be. Unfortunately the computation cost for each cycle does not decrease proportionally to the cycle size and the system can get overloaded. Moreover, this cost differs from PDA to a normal PC since they have different computation power.

Hence, in order to establish the optimal processing rate we have tested the system performance for processing cycles of one and two seconds respectively. Both types of test have been performed in the PDA and in the PC.

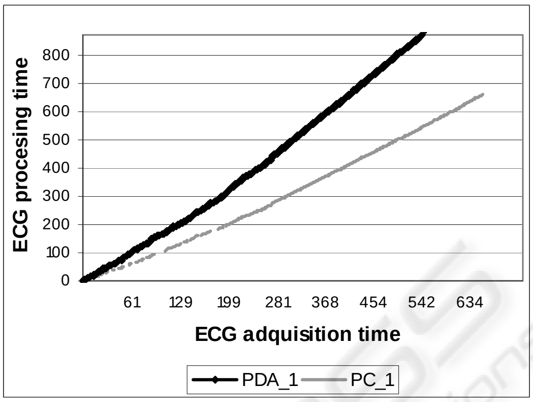

Figure 7: Processing rate of one second

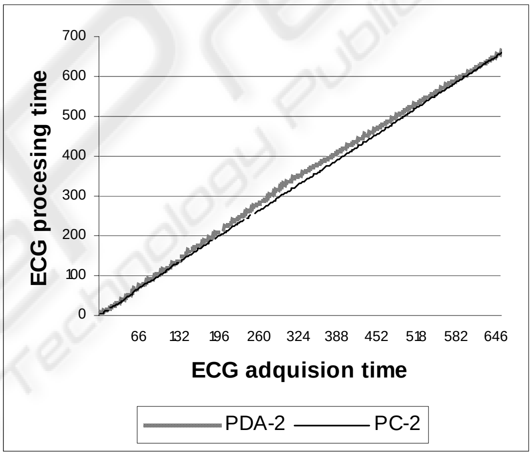

Figure 8: Processing rate of two seconds

The figures 7 and 8 show four functions: PC-1, PDA-1, PC-2 and PDA-2. Every point (x,y) of all those functions indicates that the signal package provided by the ECG Signal Acquisition at the second x is processed by the system at the second y. For PC-1 and PDA-1 functions, the entire processing cycle is of 1 second, and for PC-2 and PDA-2 functions it is of 2 seconds. In PC-1 and PC-2, the entire processing cycle is performed in the PC, and, obviously PDA-1 and PDA-2 in the PDA.

As it can be observed in the figures, in both cases the system running in the PC achieves a stable state since the corresponding functions are very close to the diagonal function (that would mean that the signal packet received at second x is processed by the system at second x). The stability comes from the fact that the difference between the diagonal and the PC-x functions does not grow along the time. In other words, the system performs all the tasks before the next signal package has been arrived. In the PDA case, for processing cycles of one second, this property is not achieved. Nevertheless, good results are obtained for processing cycles of two seconds.

As we have explained before, the package size has a direct influence on the rhythm delay detection, and therefore, in the alarm detection. The average of the time necessary to detect the rhythm for this type of packages appears in figure 9.

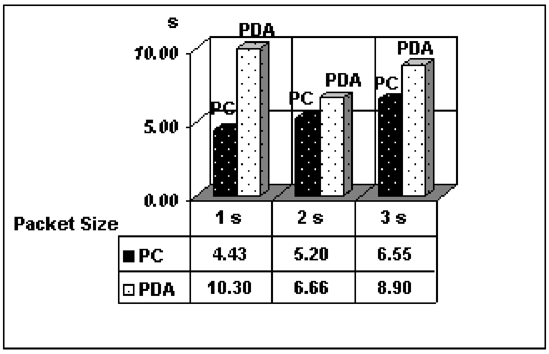

Figure 9: Rhythm detection delay

For packages of one second the PC achieves an average of 4.43 seconds in obtaining the rhythm, meanwhile the PDA needs 10.3 seconds, but, as the processing cannot be performed in real time, the rhythm detection delay would grow if the experiment duration were longer.

For packages of two seconds the PC obtains an average of 5.2s to detect the rhythm meanwhile the PDA needs approximate 6.66s to detect it.

Notice that we have also experimented with signal packages of 3 seconds and seen that real-time processing is also possible. But, as the rhythm delay time is greater than with signal packages of 2 seconds, so we conclude that the entire ECG analysis process should be performed in the PDA every 2 seconds.

Finally, an explanation of the rhythm detection delays obtained is because the detection algorithm used needs the previous beat types and the next three ones, in order to detect the rhythm for the current beat.

4.2 Alarm notification: cost and latency

The aim of this subsection is to compare the MOLEC system, which only sends alarm signals to the medical center (according to the Alarm Manager Module policy described in section 3), with a system that continuously sends the ECG signals picked up from the sensors and detects the alarm in the medical center. Supposing that a GPRS network is used for communication, we present further the communication costs for the alarm notification during 30 minutes of monitoring.

For this test we used three ECG records: the 100 record that does not contain any alarm, so there is no communication with the medical center; the 207 record that is from a patient with serious health problems and contains five minutes of alarms; and 124 record that is from a typical user, so it contains an average notifications amount. All the ECG signals used have the same sampling frequency (360 samples/second). For the system that sends all the signals we supposed that each sample has 2 bytes.

In the next figure it can be observed the amount of data that the system would send in each case.

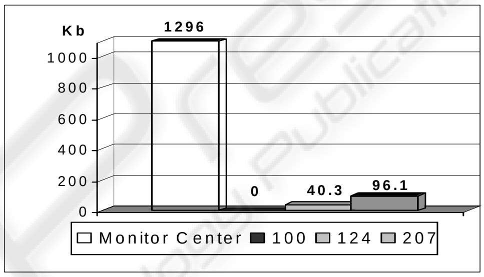

Figure 10: Communication costs

A system, that does not make any processing and compressing of the signal, would send approximately 1296Kb for each 30 minutes which means more than 2Mb/hour, meanwhile the MOLEC-PDA-Holter, in the worst case would send more than 100 times less. If no abnormalities are detected then there is no communication with the health center, as in the case of the record 100. Therefore the amount of communication with the health center is drastically reduced, and so the communication costs.

Another variable that should be taken into account is the delay between the time when the risk episode starts and the moment when the health center notices it.

The time needed for the MOLEC system to notify an alarm is

$t_{notify} = t_{rhythm\ detection} + t_{alarm\ compression} + t_{communication\ latency}$

In other words the notification delay depends on the time needed to detect the rhythm in the PDA, the time needed to compress the alarm message and the latency that the GPRS network involves in order to send it to the monitor center.

On the other hand, in the case of the systems that continuously send ECG signals to the medical center the notification delay would depend only on the communication delay over the GPRS network and the rhythm detection time in the medical center.

As it could be observed in the figure 9, the delay of the rhythm detection, with our algorithm, is greater in the PDA (around seven seconds) than in a normal PC with only one user (around four seconds). In a system with more users that continuously send ECG signals the costs to obtain the same results would be greater.

Moreover, a system that continuously sends ECG signals to a monitor center would send many, but small signal packages through the network, what means, if the connection is stable, a constant latency in the communication; meanwhile the MOLEC system sends compressed alarm messages from time to time but with a bigger amount which suppose a bigger latency to send it.

Therefore, the notification latency is a few seconds bigger in the MOLEC system but still remains in a reasonable threshold giving the possibility to the user to obtain medical assistance in time.

5 CONCLUSIONS

In this paper we have presented the global architecture of an innovative system called MOLEC that allows an on-line monitoring of people suffering from heart arrhythmias. Among the advantages of that system are the following ones: 1) Promptness: MOLEC detects anomalous rhythms, anywhere and anytime, as soon as they are produced, and sends the corresponding alarm to the hospital; and 2) Efficiency: MOLEC optimizes the use of wireless communications and PDA resources.

In order to achieve those advantages, we have designed and performed some experiments that consisted in calculating the rate of the processing cycle that the system can tolerate in order to be efficient, stable and the rhythm detection delay minimal. That time has been 2 seconds in the case of the PDAs. Special attention has also been paid in minimizing the cost of the wireless communications without increasing the delay time for the detected serious heart anomalies. That can be achieved by performing the ECG signal processing and rhythm classification locally in the PDA and by sending only alarms to the hospital.

REFERENCES

Bluetooth. 2003. www.bluetooth.com

Cardio Control.2003. www.cardiocontrol.com/cardio.htm

Daja, N., Relgin, I., Reljin B., 2001. Telemonitoring in Cardiology –ECG transmission by Mobile Phone. *Annals of the Academy of Studenica* 4, 2001.

Despopoulos, A.., Silbernagl, S. 1994, Texto y Atlas de fisiología. ISBN: 84-8174-040-3.

Dimitri Konstansas Val Jones, Rainer Hersog. 2003. MobiHealth- innovative 2.5/3G mobile services and applications for healthcare. *Workshop on Standardization in E-Health.* Geneva, Italy.

Eclipse 2003. http://www.eclipse.org/.

Farreras and Rozman, “Medicina interna”. Decimatercera edición. Edición en CD-ROM. Sección 3. Cardiologia pag 395 – 523. October, 2001.

GNU 2003. http://gcc.gnu.org/java/

Handhelds 2003. http://www.handhelds.org/.

Health Level 7 (HL7). 2003. http://www.hl7.org/.

Jané, P., Blasi, A., García, J., Laguna, P. 1997. Evaluation of an Automatic Threshold Based Detector of Waveform Limits in Holter ECG with the QT database”. Computers in Cardiology, vol. 24, pp. 295-298.

Kunze, C., Gromann, U., Stork, W., Müller-Glaser, K.D.,2002. Application of Ubiquitous Computing in Personal Health Monitoring Systems. *36. annual meeting of the German Society for Biomedical Engineering.*

Le Blanc, R., “Quantitative analysis of cardiac arrhythmias.” CRC: Critical Review in Biomedical engineeering, 14(1):1-43, 1986

MIT-BIH Database Distribution. 2003. http://ecg.mit.edu/

Mitchell, T.M., “Machine Learning.” ISBN 0-07-042807-7. Section 3: Decision tree learning. Pages 52-75.

Pan, J., Tompkin, W. J. 1985. A real-time QRS detection algorithm". *IEEE Trans. Biom. Eng.* BME-32: 230-236.

Rodríguez, J., Goñi A., Illarramendi, A. 2003. Classifying ECG in an On-Line Monitoring System. Submitted for Publication.

Rodríguez, J., Goñi A., Illarramendi, A. Capturing, Analyzing and Managing ECG Sensors Data in Handheld Devices. *DOA 2003.*

Sachpazidis 2002. @Home: A modular telemedicine system. Mobile Computing in Medicine, Proceedings of the 2. *Workshop on mobile computing. Heidelberg, Germany, 2002.*

Ventracor Limited. 2003 http://www.ventracor.com