Vital Signs Monitoring and Management using Mobile Devices

Bruno Fernandes, José A. Afonso
Department of Industrial Electronics
University of Minho
Guimarães, Portugal
jose.afonso@dei.uminho.pt

Ricardo Simões
Institute of Polymers and Composites - IPC/I3N, University of Minho, Guimarães, Portugal; and Polytechnic Institute of Cavado and Ave, Barcelos, Portugal;
rsimoes@dep.uminho.pt; rsimoes@ipca.pt

Abstract— **Constant breakthroughs in medical sensor technology and mobile devices fields, combined with growing wireless communication capabilities, have made possible the emergence of new health monitoring paradigms. The ever-increasing features of PDAs and smartphones make them a vital component in innovative health monitoring systems. In this paper, we introduce a handset mobile monitoring and management system, developed as complement to a complete vital signs monitoring project (MOHLL). The main purpose of this system is to provide physicians with real-time visualization of the patients' vital parameters, namely the ECG trace, heart rate, and body temperature, through an Internet-connected PDA.**

Keywords - Mobile Devices; Mobile Health; Wireless monitoring; Vital Signs; ECG.

I. INTRODUCTION

During the past decade (2000-2010), the expansion of mobile communication devices, such as mobile phones, smartphones or even handheld computers (PDAs), have increased to a level that turned their services into the most used ICT (Information and Communication Technology) worldwide. According to the 2010 ITU (International Telecommunication Union) report [1], by the end of 2009, there were approximately 4.6 billion mobile cellular subscriptions, with the average penetration rate, in developed countries, above 100%. This growth states the importance that these devices have taken in our everyday life, not just based on their cellular networks communications, but also in a set of tools that they have been added during the past few years. The developments, at both hardware and software levels, turned the usual mobile phones into high performance computer systems devices made to be discreet and pocket fit, capable to execute tasks that were, not long ago, associated only to PCs. Internet access, multimedia file support or the ability to develop and use third-party software applications, are some of the features present in nowadays smartphones and PDAs, due to the creation of dedicated operating systems as well as the many improvements made in their processing and memory units or in their communications systems, that ceased to allow only cellular networks communications to start providing new types of connection to other wireless networks (WLAN or Bluetooth).

All these developments have considerably expanded the number and type of possible applications for mobile devices, making them essential elements in some areas and with a huge potential for many others. The medical field is one of those areas, where ubiquitous computing appears as a tool of growing importance and the commercial applications developed for medical and healthcare systems are rising both in number and in users [2]. Remote medical monitoring is a specific area where such devices can provide a great help to doctors and general medical staff in the need of regularly check on their patients. This paper describes an approach undertaken to develop a health monitor and patient data manager based on a commercially available PDA.

The presented work is integrated within project MOHLL (Mobile Health Living Lab), a complete vital signs monitoring system for non-critical patients based on wireless sensors networks (WSNs) and standard based protocols which has been deployed in an internment floor of a local hospital. This project was designed to gather ECG (electrocardiography), SpO2 (oxygen saturation), and body (skin) temperature data and send them through a ZigBee [3] network into a central data server, where all system information is stored, before being available to be accessed through any web browser or, as this paper describes, through a PDA with WLAN connectivity and the software application developed to be used in this project.

The remainder of the paper is divided as follows. In the next section we discuss some of the related work regarding mobile devices usage in other vital signs monitoring system. In section III, the MOHLL project structure and its components is introduced. The subsequent section addresses the development details for the mobile monitoring applications. In section V, the results achieved in field testing are discussed. The final section presents some concluding remarks and future work.

II. RELATED WORK

Many approaches are being done regarding vital signs monitoring and/or analysis systems using mobile devices. The number of existing research projects and commercially available systems prove the great potential of handset devices applicability in the medical field. In the research presented in [4], there were considered to be two main architectures for ambulatory vital signs monitoring systems, which use the mobile device with a direct link (wireless, usually Bluetooth) to the wearable sensors.

The first group intends the mobile devices to gather and send all vital signs data arriving from the sensors. The sent information is then analyzed in a hospital facility. Some of the systems with this architecture may also have recording and representation functions, available in the devices. These group systems, even with real-time monitoring ability, have a great drawback due to the permanent communication needs, which reflects in high power consumption, usually unsustainable by mobile devices. Examples of this group are some commercial solutions offered by Alive Technology [5] or Vitaphone [6], as well as some research projects like Secure Mobile Computing [7].

In the second group are considered all systems with an analyzing process between the sensors and the medical centers. The intention is to continuously check the acquired vital signs for any anomaly that, when detected, triggers an alarm responsible for notifying the proper medical staff. This structure can be found in the UbiMon system [8], from the Imperial College of London, and in the MOLEC research project [9], from the University of the Basque Country.

The project described in [10], which possess other mobile device based system architecture outside the previous classification, presents the closest similarity with the MOHLL project, as it is also intended to work in hospital environment, enabling the creation of monitoring stations where all patients ECG signals should be available. A ZigBee sensor data collection network is the basis of the acquiring system, being responsible for routing all data to the project's server. The received data are then available to be visualized either through a web browser or through a PDA based application.

III. THE MOHLL PROJECT

The main objective of this project is to enable healthcare providers to access their patient's vital signs without having to be near them, through the use of monitoring units at the hospital. A permanent link to the patient's health condition when outside the hospital is also possible, which may be especially useful when the opinion of a specialist physician is needed.

The designed system was build to acquire the patients' medical data through a set of distributed sensors and make it available for visualization on monitoring screens. Unlike conventional monitoring systems, the physical link between these two components is not a data cable, being replaced by wireless networks, which make possible the remote data analyzing.

The different stages of the monitoring process can be seen in Figure 1. The system's course of action begins with the raw acquisition of vital signs data by ZigBee-based wearable sensors. After being treated, the data are sent through one of the hospital's WSNs to the Data Server. In their path, sensor's data may be routed through different spatially distributed network devices. These networks have self-organizing capabilities, as well as multi-hop routing features, allowing topology modifications in response to mobility or node failures. All acquired data are transferred through a serial interface from the coordinator to a ZigBee-to-Wi-Fi gateway computer, responsible for verifying the integrity of the data and processing them, as well as establishing HTTP connections to send the processed vital signs to the Data Server. Here, all incoming data is gathered and saved into the server database, where all system information is stored and becomes accessible to real-time visualization, through the Internet or the hospital's Wi-Fi network. Recovering patients can also have their vital signs remotely monitored at home, through the installation of a ZigBee infrastructure, as well as the required applications running on a personal computer with Internet access.

By addressing non-critical patients with constant health care supervision needs, this project intends to present a monitoring structure where patients can have a high mobility level, within the hospital facilities, while their vital signs are continuously followed. Using comfortable and unobtrusive measuring devices, placed into a wireless network with auto-reconfiguration capabilities, the developed wearable sensors provides patients with a safe monitoring system where no physical connections are needed. In addition to improving the patients' internment period, this approach also provides an accurate multi-patient monitoring and management system based on standard Web functions, enabling health care

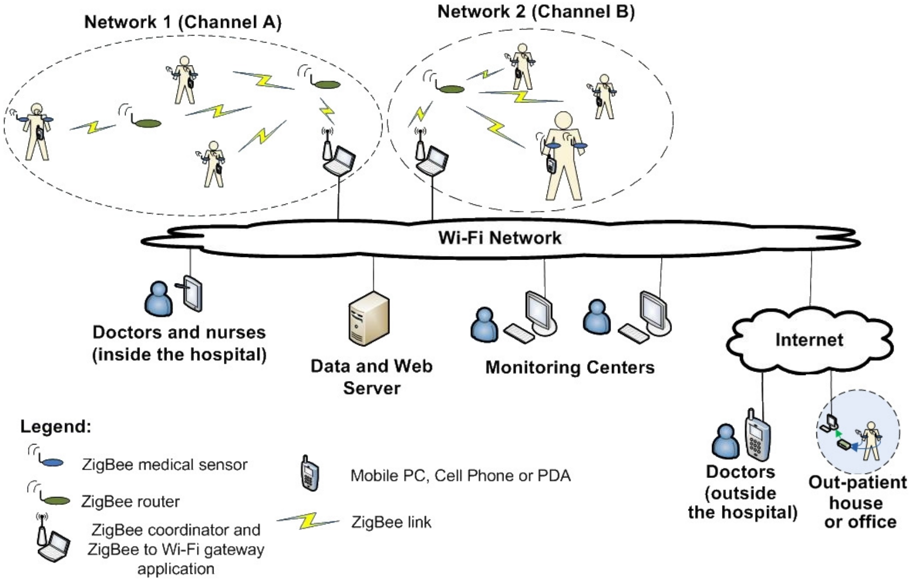

Figure 1 – System architecture overview.

providers to have a more efficient method to monitor the patients' health condition.

The system components, such as sensors, data networks, or storage and visualization applications, have been specifically designed for this project to enable seamless integration. The next sections describe each of these elements, as well as their incorporation in the overall project.

A. Sensors

Three types of vital signs sensors were developed (ECG, blood's oxygen saturation and skin temperature). However, since an algorithm to extract the heart rate from the ECG waveform was also implemented, we consider the system to have four types of physiological measurements. The sensors were designed to be small, comfortable and noninvasive devices with no physical connection to any other equipment, aiming to significantly increase monitored patients' mobility.

All sensors share the same architecture, which consists in the combination of the following modules:

- Signal acquisition module. A transducer used to convert the physical stimulus into electric signals.
- Signal conditioning module. Amplification and filtering circuits responsible for electrical signal treatment.
- Wireless communication module. Responsible for analog to digital conversion and for data transmission. The same ZigBee module is used in all measuring devices: Jennic's JN5139-001-M00 [11], with provides an integrated antenna.
- Power module. A battery responsible for the energy supply of the remaining modules. These batteries may differ, depending on the energy requirements of the sensors where they are used in.

Despite, the main structure of all senores be the same, their behavior differs according to the vital sign which they capture, e.g., the sending data rate directly influences the type of battery used and the required maintenance. The ECG sensor has to send a 50 sample message every 250 ms, while the skin temperature sensor just has one measured data value to send every 3 minutes. Therefore the power consumption, network, server processing and storage requirements are much more demanding for the ECG.

B. ZigBee Network

Factors related to power consumption, signal range, bandwidth, cost, reliability or security were some of the considered aspects during the communication method design. From this process ZigBee protocol was chosen as the most appropriated regarding the project requirements, due to the large number of nodes that could be supported, the reliable protocol stack structure, the availability of interoperable devices from several manufacturers and the reduced power consumption [12], which make the ZigBee standard specially suited for battery powered devices networks, as the one here described.

The requirements let to the implementation of a short-range wireless personal area network (WPAN) in which three different network devices coexist: end devices (sensors), routers and a network coordinator. Devices have to be able to enter or leave the network without interfering with its performance, which was accomplished by organizing the network in a mesh topology [13]. The routers are distributed over a wide area, as a hospital floor. Therefore alternative pathways are created for the data transfer between the end devices and the network coordinator, improving the network coverage and reliability.

As the end devices (sensors), routers and network coordinators were also specifically developed for the MOHLL project. Unlike the sensors, these devices must be externally powered in order to meet their energy needs, since they always must be listening for the incoming data frames. Given that they stay at a fixed position, this requirement was fulfilled without affecting the systems efficiency. Structurally identical, these two devices only have differences at the application level and at the external power provider. Routers are powered through the hospital's power circuit, while the network coordinators receive their power through a USB connection to the ZigBee-to-Wi-Fi gateway computer, which is also used to exchange the data.

Several mechanisms are used to deal with interference in order to provide reliable vital signs data transfer. Since both ZigBee and Wi-Fi operate in the 2.4 GHz band, a pre-selection of non-overlapping channels is made. During the network formation, the ZigBee coordinator performs an energy scan procedure and selects the channel with lowest interference level. During the network operation, a retransmission scheme is used to recover corrupted packets.

C. Data Server

The purpose of the Data Server is to manage all the system's information: monitored vital signs values, patient and sensor information and also system users' data and their permission levels. The running server applications are constituted by two Java servlets: the Data Reception Service (DRS) and the Data Dispatch Service (DDS). DRS is responsible for the constant receiving, validation and database storage of the incoming packages arriving from ZigBee-to-Wi-Fi gateways. The DDS servlet, on the other hand, is responsible for handling all authenticated users requests. As shown in Figure 2, these two servlets only have an indirect connection through the systems database.

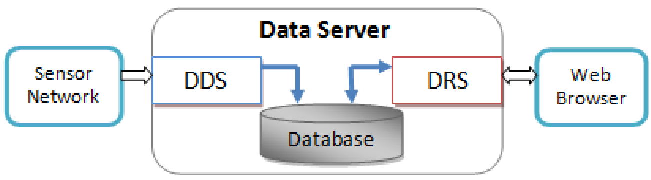

Figure 2 - Data Server architecture.

All accesses made to the server through any of the referred applications, are done using the HTTP communication protocol. The Apache Tomcat web server was used to support both servlet applications as well as a web site. This site was developed using HTML and JSP (Java Server Pages), which was used to interact with the MySQL database. Its purpose was to allow patient vital signs visualization through any web browser, as well as providing management functions for all systems elements (users, patients and sensors). The web browser's viewing area allows the simultaneously display of data from of up to six patients. To each patient is associated a Java Applet where his vital signs are represented. This option was taken to enable the integration of a set of graphical representing functions within the java web interface. Java applets run over the client computer Java Virtual Machine, and they are responsible for opening a HTTP connection to the Data Server, which is used to receive all incoming real-time data.

The use of a web browser, simplifies the monitoring process, enabling any Internet connected computer with Java Runtime Environment software to act as a monitoring station, eliminating the need for any additional software.

IV. Mobile Monitoring and Management

Considering the growing potential and given usages of PDAs and smartphones, a mobile handset monitoring concept was designed. This appeared as complement of the MOHLL project web site, and is intended to be a more practical way for healthcare providers to supervise the health condition of their patients, being able to do so without needing to access a computer, for routine check purpose, as opposed to the web site's continuous monitoring profile. One of the main reasons of this principle has to do with the battery life limitations that arise with constant Wi-Fi connectivity, in all handset devices. The support of managing operations provided by this mobile application is also very useful, especially when patients and sensors associations are made, due to the possibility of this process to be done in the patient's room.

The mobile application that was developed had to be incorporated with the previously developed server system, in order to keep the Data Server architecture as intact as possible, excluding the need for any structural modifications for mobile devices support. The adopted solution was to keep the Data Reception (DDS) and storage services and implement a server application with similar web browser support functions. Under the DRS servlet, a PDA support layer was built to handle all database connections regarding mobile monitoring applications HTTP requests. Since both the Web site and the mobile application share similar functionalities, the link between their server support systems and the database is made through a common abstraction layer, as shown in Figure 3. On the PDA end, the user interface single connections with the system's server are done through a communication class, responsible for assembling all data into a predefined structure before sending them. This class is not however responsible for the real-time vital signs data transfers due to their continuous communication profile.

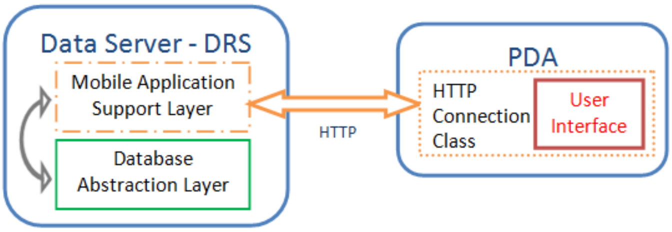

Figure 3 - Architecture of the PDA application support system

The PDA application and support functions work in the same basis as the described web site, and it displays the following features:

- User authentication system;
- Sensor managing options: insert, delete;
- Patient managing options: insert, edit information, delete record;
- Patient-Sensors association managing options, used to select which vital signs each patient will have monitored;
- Individual patients alarm configuration, used to set the normal vital sign values range;
- Real-time vital signs visualization;
- Historical vital signs data presentation in graphical format;

The vital signs visualization process is the most complex feature of the application, mainly because the demands of real-time graphical representation of the ECG signal, which, besides constant communication activity, also requires a good processing performance, in order to accurately update the data drawing. This operation, unlike all the other communication functions, is not based on a request-response configuration. In this case, only one request is made to the system's server, which establishes a permanent connection channel with the PDA. Through this channel, all the monitored patient ECG incoming data packages are continuously sent, until this connection is closed (or lost). The server is responsible for continuously checking the channel, in order to detect any breaks to this link. As previously mentioned, for every 250 ms, a 50 sample ECG values package is assembled, together with a time stamp. In the mobile application end, these packages are received by a working thread responsible for holding them and making them available to the graphical representation function. This operation has to be done in a 250 ms interval, in order to ensure the accuracy of the real-time representation. All the other vital signs are updated through a timer function that, at intervals of 500 ms, makes a request for new measurement values from any of monitored signs.

The viewing area of the application's main screen, which can be seen in Figure 4, has the patient identification at the top, followed by the ECG signal drawing region and then the numerical values of skin temperature and heart rate measurements (blood's oxygen saturation sensor has not yet been tested). The scalar vital signs values change color depending on whether or not they are within the defined interval, and if this values are outdated, they are shown in an intermittent way. For each of the three mentioned vital signs, the battery life status of the corresponding sensor is presented, to help with the sensor's maintenance. Other options like adjusting the ECG graphic zoom or the corresponding line thickness are also available, alongside with buttons to provide access to a backlog of recent vital signs records. As the real-time representation, also the historical medical records representation operations are different for the ECG and other signs. During the real-time PDA visualization of the ECG data, the incoming packages are stored into an array, which, when the user captures a peculiar cardiac event, allows them to stop representation and go back on to that particular time. As for the other vital signs, if the user wants to see a graphical representation of that signal in the previous hours (the number of hours depends on the type of signal), a request is sent to the server for the stored data measured within that time.

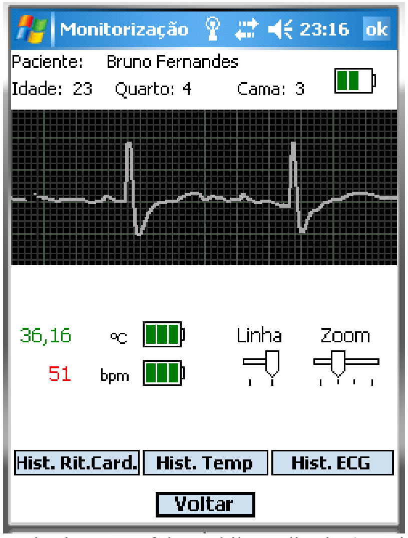

Figure 4 - Viewing area of the mobile application's main screen.

A correct wireless failure management was also an important aspect deled with, during the development phase. Since the handheld devices often lose Internet connection, due to getting in and out of wireless signal range, and in order to increase the mobile monitoring application reliability, it was created a procedure to constantly verify the connection to the server, preventing application errors and improving the on and off wireless signal situation, without lost of stability.

The described application was developed using C# and was designed for Windows Mobile handsets featuring .Net Compact Framework 3.5 software. All tests were made using a Qtek 9090 PDA equipped with a 400MHz Intel PXA263 microprocessor, 32 MB of ROM, 128 MB of SDRAM and a Wi-Fi 802.11b network capability.

The choice to use a Windows Mobile device was based on the availability of the equipment at the start of the project, and, especially, on its high market share at that time. Since Microsoft recently decided the phased out of the Windows Mobile OS, the adoption of the Android platform is being considered for future developments.

V. Field Testing Results

After a series of laboratory trials, the PDA client application was tested in a hospital environment, monitoring the vital signs of several real patients, and was found to accurately represent all incoming data; see Figure 5. In this first implementation, and due to the high graphical processing demands, it was detected that if the monitoring window was active for over one minute, the real-time ECG visualization may get a small delay. This delay averages 5 seconds for every minute. However, since this monitoring application is intended for short time data visualization (either when a particular event occurred, or for a short period at each patient during a doctor's round), this drawback does not pose a serious hindrance to the system's objectives. This problem can, however, be reduced with the improvement of the coordination time between the receiving of packets and their representation. All other data visualization and managing functions worked as they were expected to, with no detected difficulties.

A particular aspect of the performed tests was to understand how the PDA battery life would be affected by the running application. On the utilized PDA, using the monitoring feature of the application for 10 minutes (on good Wi-Fi conditions) made the battery drop 7%. Comparatively, normal usage for 10 minutes, on average, leads to a battery loss of only 3%. This is not a problem, since this monitoring system was designed to be helpful in patient routine checks, and not as a continuous monitoring process.

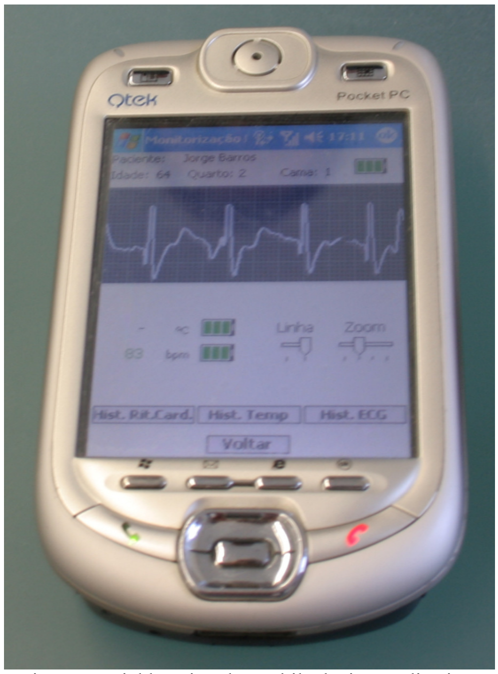

Figure 5 - Field testing the mobile device application.

The clinical staff that tested the device stated that it was easy to use and that the visualization feature was perceptible and clear. It should be mentioned that in early interactions between the research team and the medical professionals, they had made several suggestions that were incorporated into the application. The primary suggestions included the previously mentioned features for zoom, line width, and access to a recording of recent vital signs. However, other features were later added for practical use, namely, the need to display battery charge for each sensor.

Figure 6 - Mobile device application being tested by the clinical staff.

VI. CONCLUDING REMARKS AND FUTURE WORK

In this paper we describe the development of a real-time vital signs monitoring system and its management, using a standard communications mobile device such as a PDA. This system was integrated into an ongoing project (MOHLL), which is deployed in a hospital internment floor for vital signs monitoring through a web browser. ECG, heart rate and skin temperature sensors were tested. The mobile system applications are linked to the MOHLL Data Server through a wireless Internet connection based on HTTP protocol messages. The PDA developed application enables healthcare providers to check their patients' vital signs as well as manage all data related to them. Using the server's IP address, the client application establishes a connection to the mobile supporting functions contained therein, which are responsible for the database accesses and, therefore, all the system's information. Despite some graphical device limitation, all the monitoring and management function presented good practical results when submitted to field testing in the hospital environment. However, further testing is required and more extensive and demanding trials will soon be conducted. On the other hand, only casual opinions were gathered from clinical staff, and a more formal medical opinion is still needed, particularly concerning the ECG graphical representation.

Another potential improvement aspect is that the developed mobile application was designed for Windows Mobile operating system (OS) only, which has recently been replaced by the new Windows Phone 7. Considering all other mobile operating systems currently available, future work will expand the mobile monitoring system for other OS, such as Android or Windows Phone 7. Other perspective of future work is to explore the capabilities of more recent smartphones, such as java allowance, which, with the increasing processing power of these devices, may enable the use of mobile web browsers as the remote device monitoring interfaces.

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