A PDA-based portable wireless ECG monitor for medical personal area networks

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Abstract—This paper describes the development of a remote monitoring system for ECG signals. In order to achieve this goal in an economic way, we suggest the implementation of portable monitors based on consumer products such as PDA and digital acquisition cards. Several patient health monitoring scenarios where this platform may be applied are outlined, and a versatile system architecture design to fit them all is proposed. The system provides remote monitoring of one or several patients wearing a portable device equipped with wireless connectivity based on different technologies such as bluetooth, WIFI or UMTS.

I. INTRODUCTION

In recent years, major advances in the field of mobile communications have lead to the deployment of packet data services over cellular mobile systems, giving support for the development of new applications. At the same time, the spectacular rise of the number of subscribers to mobile telephony systems has sponsored the proliferation of a wide range of wireless handsets. The popularization of such devices has promoted a growing interest to continuously improve their features and performance, and therefore an increasing effort have been devoted to the development of low power and high performance embedded microprocessors with multimedia capabilities. Similarly, a significant enhancement of the development tools and software support for these platforms has been achieved. As a result, Personal Digital Assistants (PDA) and Smartphones delivering capabilities comparable to those exhibited by desktop computers only few years ago, including wireless Internet access and multimedia support, are nowadays available. These handheld devices are provided with an operating system to support application software, making easier the development and integration of third-party software. This framework opens the door to the emergence of a wide range of innovative applications that can be supported by current PDAs and smartphones, devices which are becoming more and more popular and familiar for standard users.

Among the novel applications that can be supported by the new capabilities of mobile handsets, those related with health care and telemedicine are gathering a growing expectation, because of their social relevance and the huge potential market represented by the ageing population of developed countries [1]. Accordingly, ubiquitous health care monitoring, also known as m-health, is currently an active area of research. The work presented in this paper is focused on this particular field, showing the development of a wireless portable electrocardiogram (ECG) monitor prototype based on a commercially available PDA. This subject is being addressed by many other research projects, but they usually focus on a proprietary design rather than on generic hardware integration. A description of a full-custom design with a similar functionality than the application described in this paper and additional pointers to other development projects can be found in [2], [3] is another example of multiparameter mobile medical monitoring system specific design.

This document is structured as follows: Section II present an overview of both the monitoring application and the suggested utilization scenarios. A design of the system architecture to cope with the different scenarios displayed in the previous section is subsequently proposed in section III. Section IV summarizes the prototype development and the results of the executed tests. Finally, section V derives the conclusions and suggests future trends for further development.

II. SCOPE AND SCENARIOS

This paper focuses on the development of a portable signal acquisition system with wireless connectivity. In order to minimize the development effort and the initial cost of the prototype, commercially available handheld devices and data acquisition cards have been considered for the design rather than specifically designed hardware. Nowadays, different manufacturers offer PCMCIA data acquisition cards providing the necessary hardware for analog signal conditioning and digitization. On the other hand, PCMCIA expansion sleeves are also usually available for common PDAs, and therefore the previously mentioned data acquisition cards can be easily connected to a handheld device to build a portable data acquisition system (see fig. 1).

Given the growing expectation for this kind of devices, several manufacturers currently offer proprietary software development tools for programable instrumentation based

![Fig. 1. Portable signal acquisition system based on a PDA device](image)
on PDA [4]. Nevertheless, in the design presented in this paper free open-source development tools have been selected to avoid both, software license restrictions, and constrains to specific hardware.

The integration of the PDA and the data acquisition card can give support to multiple applications. This paper proposes how to use this platform to develop a wearable electrocardiogram monitor with wireless connectivity that can be used in a wide range of situations. A similar application developed with proprietary development tools can be found in [5].

The proposed platform could be applied to different ECG monitoring scenarios, as shown in figure 2. The simplest one (Fig. 2.A), corresponds to a portable monitor (usually known as Holter monitor) attached to the patient in order to visualize or record his electrocardiogram. However, fairly more complex scenarios can be set out by taking advantage of the wireless connectivity of the PDA to support remote monitoring. Using a short-range wireless interface such as Bluetooth, it would be possible to control the monitor operation and visualize the acquired signals from a remote handheld device operated by the medical staff (Fig. 2.B). Wireless connectivity also enables other scenarios, for example, different devices could be controlled from the same desktop computer, allowing simultaneous monitoring of several patients in a centralized emergency management system (Fig. 2.C). Other wireless technologies can be used to improve the transmission range. For example, UMTS connectivity would allow patient monitoring from any location. Finally, enabling web access to the data gathered by the centralized server would allow the medical staff to remotely check the status of the patients (Fig. 2.D).

The application described in this paper benefits from a modular design so that it can be adjusted to deal with the different scenarios. In order to limit the developing effort, the different modules should be designed to be as reusable as possible in the different situations. The proposed architecture is described in the following section.

III. SOFTWARE ARCHITECTURE

This section specifies the system architecture and depicts the tools selected to implement the different modules. Linux operating system has been selected as application framework for either PDAs and Desktop/Server computers. Using the same operating system for all the devices allows to reuse most of the code when porting the application from one platform to other. At present, the Linux kernel has been successfully ported to a wide range of microprocessors, including the ARM architecture which is generally used in contemporary Smartphones and PDAs. Several Linux distributions for embedded systems are suitable for these devices. In our development we have chosen Familiar 0.7.2 [6], which is specifically fitted for HP IPAQ PDAs.

Another reason to select Linux as the operating system to develop and deploy the application is the existence of an expanding collection of free development tools, support libraries, and open-source application projects. One of the most relevant tools for our project is COMEDI [7], which provides support for data acquisition. This tool comprises a collection of drivers for a variety of common data acquisition boards, as long as a development library which offers a common programming interface to grant acquisition hardware interchangeability. This tool is free open-source software in contrast to the proprietary data acquisition support tools for Windows CE. Although originally intended for standard PCs, COMEDI has been successfully ported to the PDA platform within our project.

The application architecture is summarized in fig. 3. Nearly all the application modules are connected through TCP/IP sockets so that they can run in the same computer as well as in remote ones. The different modules can be executed either in a PDA device or in a desktop/server computer depending on the selected scenario. The use of TCP/IP also grants a transparent PDA connectivity through different wireless technologies such as Bluetooth, WIFI or UMTS.

The acquisition server module is a process running in every PDA device, and is in charge of the configuration of the acquisition hardware for analog signal conditioning and digitization. This module performs such operation as response to requests sent by a client application through the socket interface. By using this socket the server can also transmit to the clients the samples acquired from the signal in real time. The server module can handle two different request groups: configuration commands (used to setup the acquisition, i.e., the sampling period, number of analog channels, amplifier gain, single-ended or differential input, etc.) and operation commands (used to request operations such as starting or stopping the real-time sampling). This module has been developed in C using the COMEDI API. The server is designed as a multithreaded application to enable simultaneous connections with multiple clients. In such situations, only one client is enabled to setup and change the acquisition configuration, but the acquisition server sends a copy of the sampled data to every client, so that the signal can be visualized in all of them.

The graphical client module provides the user interface of the application. Using the graphical client, the user can
control the signal acquisition process, set up its parameters and visualize the signal waveform in real time. The client uses the socket interface in order to send configuration and acquisition requests to the server running on the PDAs, as well as to read the sampled data. The graphical client has been developed in C++ using the QTE graphical libraries from Trolltech [8]. These libraries are the core of a graphical user environment for PDAs named OPIE, which is included in the Linux Familiar distribution. They are also compatible with the QT libraries, which in turn are the basis of the KDE graphical environment for desktop computers. This speeds up the graphical client migration from one platform to the other. Because of the socket based interface, the graphic client can be run either in the same PDA than the acquisition server or in a remote system, thus supporting the deployment of the application in some of the different scenarios (A,B and C) suggested in section II. To enable the simultaneous monitoring of different handheld devices from the same desktop, the graphical client is also multithreaded. One thread is necessary to handle the communication with each monitor device, and an additional thread is used for the user interface.

The web interface module provides to the application the necessary capabilities to deal with the latest scenario (D) proposed in section II. Including this module in the application makes possible the remote access to the application through a web browser. This module has a similar functionality than the the graphical client, but has a main advantage: it allows remote access through the internet with no need for software installation in the terminal computer. As illustrated in fig. 3, different elements are assembled together to construct the web interface module: a resident application (monitoring daemon) developed in C, and the Apache web server with the PHP module enabled. The user interface management is accomplished by means of PHP scripts executed by the web server. These scripts handle data sent by the users through web forms, send requests to the local monitoring daemon and generates dynamic HTML pages displaying the results. The monitoring daemon processes the requests from PHP scripts and directs the necessary configuration and operation commands to the acquisition servers running on the PDA devices. The monitoring daemon must also handle and store the data samples submitted by the acquisition servers so that it can be read by the PHP scripts and displayed through the web interface. The web interface module is intended to be executed in a server computer, but it can also be run in a standalone PDA device, allowing to configure and control it through a web interface.

As previously commented, process intercommunication is accomplished through a TCP/IP interface. Data privacy is a key issue in telemedicine systems, and must be considered when sending data through a wide area network. No encryption mechanisms has been included in our application prototype, but it can be easily achieved by means of SSH tunnels and virtual private networks (VPN) applications, both of which are supported by the Linux operating system.

![Fig. 3. Application architecture](image)

**IV. DEVELOPMENT AND TESTS**

The different application modules described in the previous section have been developed and tested on a particular testbed. However, it is expected to be portable to other platform and adaptable to different scenario. This section summarizes the reference framework where the application has been tested.

To develop the portable monitor prototype the HP IPAQ H3970 PDA has been used. This handheld device is equipped with a 400 MHz ARM XScale PXA255 microprocessor from Intel, 64 MB of RAM, 48 MB of Flash ROM and it includes a class-2 bluetooth interface. This PDA model supports the Familiar Linux distribution for ARM processors. This Linux distribution can be installed in other models, and therefore, the developed application should work for similar platforms. A PCMCIA expansion sleeve from HP is used to connect the data acquisition card.

To provide signal conditioning and digitization support we have used the PCM208H PCMCIA data acquisition card from Superlogics. This card is particularly interesting
because it comprises not only the digitization hardware but also an analog signal conditioning pre-stage. The A/D converter features a resolution of 12 bits and a sampling frequency of 100 kS/s. The analog conditioning stage includes a 1-1000 variable gain amplifier, and therefore external conditioning circuitry is not required. It should be noted that if no additional circuitry is added, some digital signal processing must be applied to the sampled signal in order to reduce the noise, and, specially to reject the 50 Hz harmonics induced by power lines. This is done by the client software in our application. The card support up to 4 differential analog channel, and therefore can be used to acquire a basic three lead electrocardiogram. A driver for this card is supplied by the COMEDI system. Since COMEDI system gives support for other card models, and provides a common programming interface for all of them, our application can presumably operate with different cards. The acquisition hardware interchangeability has been successfully tested for the DAQ 6032E card from National Instruments. This card includes a 16 bit resolution A/D converter, but the gain of the analog conditioning stage are much lower, so external conditioning hardware would be necessary to acquire ECG signals. Nevertheless, the developed application runs properly for this platform.

The graphical client application has been tested both for PDA and Desktop computers. Fig 4 shows the interface for a desktop computer, whereas fig. 5 displays it running in the PDA. Three different test scenarios has been considered to test the remote management of the portable monitor prototype: i) Use the bluetooth interface of the PDA to enable remote access from a desktop PC or another PDA, ii) Attach the PDA to the corporative local area network using a WIFI PCMCIA card supported by the Linux Distribution; and iii) Establish a UMTS data session using a 3G terminal connected to the PDA through a bluetooth RFCOMM link. Most of the traffic volume exchanged between the portable monitor and the remote graphic client correspond to packets carrying real time samples. Naturally, the required bandwidth depends on the number of analog channels, the sample format (16 bit integer) and the sampling rate. Also some overhead exists due to the TCP/IP header, although it is minimized by grouping in packets of up to 500 samples. The sampling rate required for basic ECG monitoring is not much demanding (about 1 kHz), and the number of required channels is three, so the bandwidth offered by the tested interfaces is enough for the requirements (about 48kbps if the TCP/IP overhead is neglected). However, compression algorithms for ECG signals should be included in future versions of the application to improve the performance and reduce the transmission costs through the UMTS interface, where the billing is based on data volume.

Finally, the correct operation of the web interface has been checked, verifying the remote access to the system from different browsers.

V. Conclusions

This paper summarizes the development of a real-time remote monitoring system for ECG signals based on consumer electronic devices such as PDA and data acquisition cards. The monitoring application has been split into reconfigurable modules to maximize its versatility. The application supports the remote monitoring of ECG signal using two different user interfaces, a graphic client application and a web page interface. The application has been designed so that different wireless links technologies can be used to enable the remote control of the portable monitors. Several data acquisition cards from different manufacturers are also supported.

The described system is a prototype under development and can be still substantially improved. One aspect that should be addressed is the acquisition hardware. The design of a signal conditioning and acquisition module based on a low power microcontroller connected to the PDA through a serial interface is a good alternative to PCMCIA acquisition cards, which are too expensive for mass production. The integration of other biosignal sensor devices connected wirelessly to the PDA by means of a bluetooth virtual serial port is also a profitable line of research. Digital Signal processing in different stages should also be enhanced: On the one hand ECG signal compression would be recommended to reduce the traffic volume generated by the monitors; On the other hand, algorithms for automatic symptom analysis, cardiopathologies detection and emergence alarm triggering, should also be included to improve the system functionality. The integration of the application with the Hospital information management system should also be explored.

Acknowledgements

This paper has been supported by the Spanish CICYT under public research contract No TEL2003-07953-C02-01.

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