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Integrated platform for continuous monitoring of children with suspected cardiac arrhythmias

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***Abstract*— Children with cardiac arrhythmias constitute one of the most difficult problems in cardiology both in terms of diagnosis and management. In such cases continuous monitoring of ECG vital signs and environmental conditions can significantly improve the identification of a possible arrhythmia. In this study we present the design and development of a system which enables the continuous monitoring of children, from the hardware and software perspective. The system is able to carry out real-time acquisition and transmission of ECG signals, and facilitate an alarm scheme able to identify possible arrhythmias so as to notify the on-call doctor and the relatives of the child that an event may be happening. In-house monitoring of a child is performed using a sensor network able to record and transmit ECG and the living conditions, while outside the house, monitoring is performed through a GPRS/UMTS enabled device. The transmitted information can be accessed through a web based platform which facilitates basic an electronic patient record module and continuous display of monitoring information of the patient. The system design and development steps are finished and the initial tests performed on healthy volunteers proved to be very promising.**

Index Terms — *mobile health, sensor networks, home monitoring, children arrhythmias.*

I. INTRODUCTION

Telemedicine has been used for many years in order to improve health care provision or for patient monitoring solutions. Several issues such as the computational capability, size of the devices, power efficiency and cost have been limiting the availability of devices and services to a few special cases [1], [2]. Recent advancements in communications and computer systems can help us develop general-purpose systems that are more efficient, much smaller and at lower costs.

In this study, we will focus on the continuous monitoring of children with suspected cardiac arrhythmias. Arrhythmia is one of the most difficult problems in Cardiology both in terms of diagnosis and management. The problem is

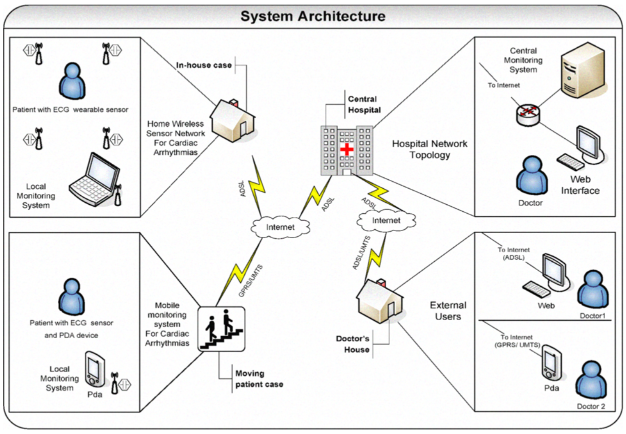

Fig.1. Overall system Architecture © IEEE 2007 [6]

particularly pronounced in Pediatric Cardiology because of the variety of etiologies and the difficulty that the children are having in trying to communicate their symptoms. For example in the case of hypertrophic cardiomyopathy, it is known that children are at higher risk for arrhythmias and sudden death than adults. In most of the cases an ECG tracing is required and this is sufficient for an accurate diagnosis, whereas in some cases, a more sophisticated modality is required [1], [3].

As an example, a relatively recently recognized rare form of cariomyopathy, the Isolated Noncompaction of the Left Ventricle (NCLV), poses new challenges. A subset of patients with this disease are especially prone to arrhythmia and sudden death. Current testing with the Holter monitor has proved insufficient because it is limited to 24 or 48 hours of recording during which the patient may be asymptomatic. Some of these children are high risk for sudden death and at the same time it is very difficult to decide for the proper treatment, making their ECG monitoring a very important task[1], [4].

In order to monitor these children sufficiently we need a noninvasive or minimally invasive way to record the ECG for extended periods of time and at the same time perform automatic analysis continuously or at frequent intervals.

Work presented here is a significant extension over our earlier telemedicine work in real-time ambulatory monitoring systems [5].

II. METHODOLOGY

In general the problem has been divided into two cases. The first one, called "In-house case" where the subject is located in his/her house. While for the second, called "Moving patient case" where the subject might be located anywhere else. Our goal is the continuous 24 hours monitoring of the child.

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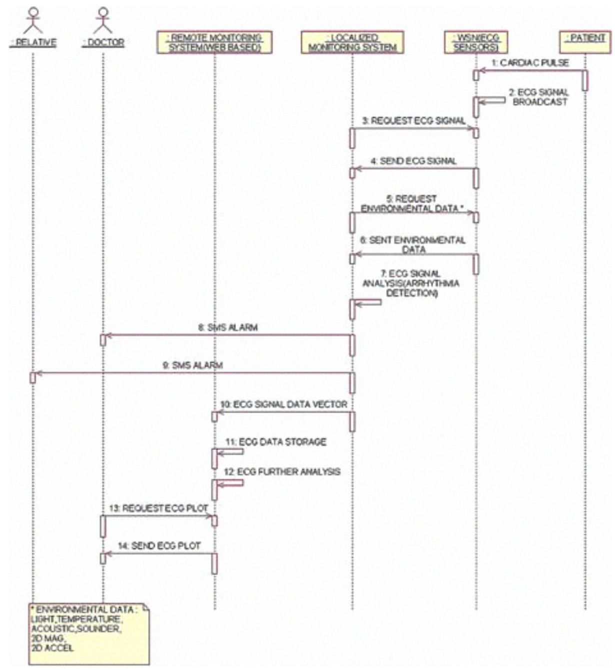

Fig.2 UML – sequence diagram of the actions being performed during the in-house case© IEEE 2007 [6]

An overall architecture diagram of the proposed system can be seen in Fig. 1. On the left hand side the two cases of patient monitoring are displayed; while on the right hand site the doctors and the access to the system are displayed.

A. In-house case

During this case,(a UML diagram describing the actions sequence for this case can be seen in Fig. 2) a sensor network is installed in the child's house that will be used in order to continuously monitor ECG signals from the patient [6] – [10]. Several other environmental parameters like light, temperature, sound, acceleration are also monitored so as to continuously check the living conditions. The ECG (3 lead) signal is recorded by a sensor carried from the child, that is part of a wireless sensor network (WSN) installed in the house. The ECG sensor has been specially designed & developed by SignalGenerix ltd (http://www.signalgenerix.com) (see Fig. 3). Signal information from the wearable sensor is propagated to a local monitoring station which will also act as a gateway to the rest of the monitoring network.

The cardiac pulse is propagated through the WSN to the local monitoring station with an embedded broadcast algorithm.

The local monitoring station is responsible for collecting environmental measurements (e.g. temperature, 2D accelerometer, sound, light):

- Sample the ECG signal.
- Store the sensor data locally.

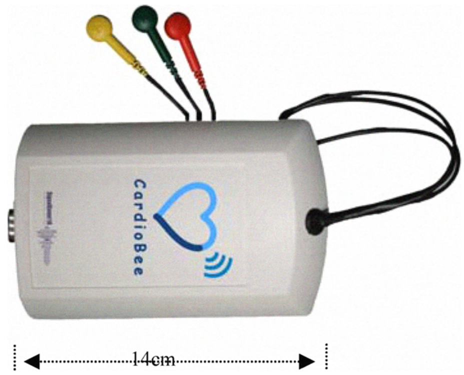

Fig. 3. Picture of the ECG recording device (ECG acquisition board and sensor note)

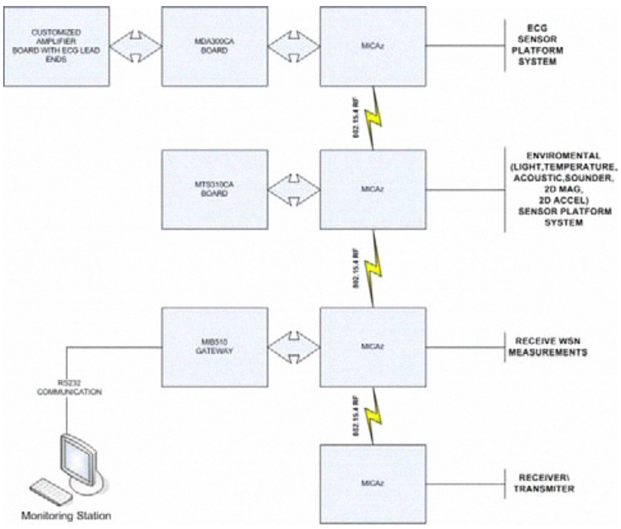

Fig. 4. Block diagram of the in-house wireless sensor network © IEEE 2007 [6]

- Analyze the ECG signal in order to detect possible cardiac arrhythmias.

In the case of a detected arrhythmia:

- Send an alarm message to the central monitoring station (located in hospital), to the supervising doctor and a relative.

For our case we have chosen to develop a Mote-based sensor network based on Crossbow® equipment [10], [11]. The proposed network that will be used to cover the patient's house is based on motes like MicaZ™ while the acquisition of ECG data is performed through a custom created board connected to the MDA300CA™ acquisition board. Additional environmental data will be collected through the MTS310CA™ sensor board. All collected information will be transmitted to a gateway, MIB510™ connected on a Personal Computer; this is going to be the local monitoring system(see Fig.4).

B. Moving patient case

The second case is more general and will be used in order to complete the coverage of the system. For this case, the

Fig.5. Snapshot from a sample transmitted ECG signal with the analysis points

child is monitored using the same ECG recording device (Fig. 3) but the signals are transmitted, through a PDA, directly to the central monitoring system (for the test pilot case an HP iPAQ hw6915 was used). The transmission is performed through the use of 2.5G and 3G mobile communication networks (GPRS/UMTS) [1]; depending on the equipment and network (see Fig. 1).

The information is stored locally on the PDA and then transmitted to the central station. The central station is responsible for the storage, analysis and display of information, as well as the notification of the on-call doctor and the relative in case of an alarm.

For both cases the central monitoring station is responsible to:

- Store data sent from the local monitoring station.
- Display data transmitted from the local monitoring stations and through a web interface.
- Analyze the ECG signal further (send a message (SMS, e-mail etc.) to the doctor).

C. Variable rate ECG signal recording

The continuous-time monitoring is limited by the available battery power. In order to achieve better results and more time of transmission we propose the use of a variable-rate signal processing system that will be used to reduce the power requirements by reducing the sampling rate during normal operation, while saving the high sampling-rate and transmission during a possible arrhythmia session. To recognize the power savings, we note that power consumption is directly proportional to the frequency of operation. Thus, we can reduce power consumption by increasing the sampling period T_s. We can show that without changing the anti-aliasing analog filter prior to sampling, using a digital filter of variable bandwidth BW, we can produce a properly sampled ECG signal, sampled at $2(1-1/BW)T_S$. Furthermore, larger sampling periods can be accommodated by varying the analog cutoff frequency of the anti-aliasing analog, lowpass filter. Here, we note that we do require continuous transmission of one lead of ECG signal. For the case of a moving patient, three leads will be acquired and stored on the device, but only one waveform will be transmitted continuously [9]. This will result in power savings due to the reduction in transmission power requirements.

D. ECG Acquisition

CardioBee (the name of the ECG acquisition device) is a portable and low cost ECG Acquisition system capable of acquiring ECG signals and transmitting them via wireless (zigbee) technology to a PC. The device (Fig. 2) can be easily adapted on the patient's body, using two common straps, without disturbing his movements. Being optimized to be used by patients with needs for home-based monitoring, its performance requirements include more than 10 meters transmission range (repeaters can be used to extend this range), very low package loss and more than 4 days power autonomy (with 4 AA rechargeable batteries).

The ECG recording circuitry has been designed so as to be able to deal with the extremely weak nature of the ECG signal as well as with the different noise sources appears during measuring. In particular the hardware design meets the following requirements: It must be able to measure low voltage signals in the range of 0.05 – 10mV, have flat frequency response at the band 0.05 – 150Hz, high Common Mode Rejection Ratio (CMRR), very low input leakage current (< 1 micro-Amp), very high input impedance (> 5 Mega – ohms) and it must remove AC mains noise. In order for the acquisition system to meet the above requirements, the signal acquisition chain consists of several sub-circuits/components.

CMOS Buffer/Preamplification: A CMOS preamplifier op-amp circuit with extremely high input impedance serves as an ideal decoupling stage between weak body signals and the rest circuitry.

Instrumentation Amplifier: A high precision, low noise instrumentation amplifier is used having very high Common Mode Rejection Ratio and input impedance.

Active Grounding Circuit: Implemented by taking the average (common mode) of the two pre-amplified input signals and, after amplifying and inverting it, feeding it back as the ground (reference voltage) for the circuit.

High-Pass Filtering: An eight-order Bessel filter with a cut-off frequency of 0.05 Hz.

Secondary Amplification: This second amplification stage further increases the SNR and also boosts the signal voltage to a range of 0-2.5V, appropriate for sampling with the A/D acquisition board used.

Low Pass Filter: A cascaded RC filter with cut-off frequency of 150 Hz.

E. ECG Digitization and Transmission (sensor network)

The digitisation and wireless transmission process is performed by the MPR2400 Wireless Node of Crossbow [12] equipped with a microprocessor, an MDA300 Data Acquisition Board (Crossbow) and Zigbee RF module. The whole process is fully programmable and customizable based on the patient's needs. The signal is digitized using a 12-bit ADC with a rate up-to 250 samples/sec. The transmission is performed using a powerful ad-hoc protocol capable to dynamically compute the optimum route to the Base/Pc via the several repeaters, as the patient moves in the house, minimising the package loss rate.

F. ECG Analysis and Transmission

For the ECG analysis needs of our project we use the open source QRS Detection software provided by E.P. Limited online at [13]. The software uses two modules. The first one is the QRS Detection which includes the QRS detection functions and the QRS filter functions. The second is the beat classification module which is used for beat classification and detection.

For the ECG signal transmission between the in-house network and the remote monitoring system the asynchronous xml communication protocol proposed in [7] is used.

III. RESULTS

Several tests were performed in order to verify the correct transmission of data over the system. . The first set of tests was for the in-house use of the system. Tests were performed using the ECG simulator with a sensor node connected to the gateway [7].

Additional tests were performed to ensure the correct functionality of the system using two repeaters, and positioning the sensors at various distances from each other, including various obstructions between them. Examples of these experiments showed that the greater the distances, the bigger the packet loss (that was somehow expected), but bigger loss was observed when there were more obstructions (for instance, when the two sensors were in different rooms, and the doors connecting the rooms were closed) (see Table I).

TABLE I. RESULTS WITH REPEATER IN SAME ROOM WITH GATEWAY (DISTANCE 5M) AND PATIENT SET IN A DIFFERENT ROOM (WITH TWO WALLS OBSTACLE BETWEEN THE REPEATERS)

Packets Sent	35495
Packets Lost	22001
Retransmissions	56549
Forwarded	7071

Although these tests ensured the correct functionality of the sensors, more real life and realistic experiments were carried out. After testing the system with a moving patient in the same room (just to see if the device could receive the human ECG), we got to test the system with a healthy patient, in a house, in an effort to simulate the real life usage of the system. The patient was behaving normally, moving freely in the house (which had an area of 200 sq meters). We managed to record many hours of normal ECG, with acceptable noise levels, since we could run the analysis algorithm and analyze normal ECG. After many trials and error attempts, we located the best spots to achieve coverage of the whole house with just two repeaters in addition to the base (see Table II.

TABLE II. RESULTS WITH REPEATER IN A DIFFERENT ROOM WITH THE GATEWAY (AT A DISTANCE OF 8M) AND PATIENT SET IN A THIRD ROOM (AT A DISTANCE OF 4M FROM THE REPEATER)

Packets Sent	20175
Packets Lost	62
Retransmissions	2140
Forwarded	19542

IV. CONCLUDING REMARKS

Concluding, a prototype m-Health system for monitoring children with possible arrhythmias was developed, implemented, and tested. It is anticipated that through the use of the proposed system we will be able to help pediatrics cardiologist in the identification of the arrythmia, thus helping the physician prescribe a proper treatment. We have provided the architecture description and all the hardware tests for the system. Future work will cover the complete live testing of the system with all actors (healthy subjects, patients, doctors, and parents) involved, in order to ensure the flawless functionality and robustness of the system.

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