Journal of Universal Computer Science, vol. 12, no. 1 (2006), 30-44
submitted: 6/5/05, accepted: 13/12/05, appeared: 28/1/06 © J.UCS

A New System Dedicated to Real-time Cardiac Arrhythmias Tele-assistance and Monitoring

Haiying Zhou, Kun Mean Hou, Laurent Gineste, Christophe De Vaulx
(Laboratoire LIMOS UMR 6158 CNRS, ISIMA, University of Blaise Pascal, France
hyzhou, kun-mean.hou, gineste, christophe.devaulx @isima.fr)

Jean Ponsonnaille
(University hospital of Clermont-Ferrand, France
jponsonnaille@chuclermontferrand.fr)

Abstract: More than 60,000 people die suddenly each year in France due to cardiac arrhythmias. The current techniques used to diagnose cardiac arrhythmias such as HOLTER, R.TEST and telemetry system are partially efficient owing to the limitation of the duration of monitoring. This paper presents a new system dedicated to real-time cardiac arrhythmias tele-assistance and monitoring. This system is generally composed of 4 main configurable elements: wireless ECG sensor, local access unit, remote centre server, and remote surveillance terminal. The main technical challenges of this system include three aspects: a real-time automatic ECG diagnostic algorithm, an embedded real-time multi-task operating system, and a real-time reliable telemedicine communication protocol. This paper gives our solutions to these problems and specifies the technical details. Currently, this system has been evaluated on thirty patients at the CHRU of Gabriel Montpied hospital (Clermont-Ferrand, France) and also been used to test the athletes' cardiac status during the physical exercises. The performance results show that this system meets fully the requirements of real-time cardiac monitoring and diagnosing application and can be used as a long-term cardiac healthcare equipment.

Keywords: Real-time telemedicine, wireless ECG sensor, cardiac arrhythmias, Automatic ECG diagnosis, Embedded Micro-kernel
Categories: C.2.0, C.3, H.4.3, J.3

1 Introduction

In spite of the rapid development of pathological research and clinical technologies, cardiovascular diseases are still the number one killer: they cause one death out of three in the world [WHO, 03]. Each year, there are an estimated seven million deaths around the world and more than 60,000 deaths in France due to cardiac arrhythmias.

Most of them are sudden cardiac deaths after myocardial infarction and 90% of them are due essentially to cardiac arrhythmias. 20% of sudden cardiac arrhythmias deaths are caused by heart block or pause (bradycardia) and 80% are caused by ventricular fibrillation (VF), frequently initiated by ventricular tachycardia (VT). The principal aetiology of sudden death for adults is due to myocardial infarction. For the group of population having a coronary pathology and chronic ischemia, the risk of death is particularly high.

The "massive heart attack" is generally considered as an unpredictable and unpreventable event. In spite of the effectiveness of the post-heart-attack treatment, a lot of patients die because heart attacks occur suddenly without a shred of warning. Recent studies show that there are generally significant cardiovascular abnormal symptoms such as palpitations, faints, chest pain, shortness of breath etc., before the sudden occurrence of a heart attack. If these abnormal symptoms can be early detected and diagnosed, time is saved to prevent the occurrence of heart attack or to provide an efficient treatment in time. Therefore, to reduce the number of disabilities and deaths caused by heart attack, it is necessary to have an effective method for early detection and early treatment.

The most effective preventive therapy of sudden death due to cardiac arrhythmias is the implantation of an implantable cardioverter-defibrillator (ICD). By producing a series of orderly and strong electrical shocks to adjust cardiac rhythm to effective status, ICD helps to treat cardiac disorders such as VF, VT, and atrial fibrillation/ flutter. However, the high cost of ICD implantation prevents it to be widely applied. Moreover, ICD is also an invasive technique requiring a major surgery with potential complications, including venous access, lead placement, intravascular thrombosis/fibrosis, and generator [Ellenbogan, 92].

ICD is mainly applied to the high risk of death patients who have cardiac arrhythmia especially VT or VF, when the risk is accurately identified. Nevertheless, recent surveys discover that sudden cardiac death does not only happen to people who have had heart attacks (myocardial infarction) in the past, but can also happen to young people who were entirely well until they died [IME, 02]. Therefore, it is necessary to develop a portable home-based cardiac surveillance system to provide long-time continuous cardiac monitoring service. This system should be cost-effective, risk-free and easy to use in everyday life.

2 State-of-the-Art: cardiac monitoring systems

The ECG (electrocardiogram), the body-surface manifestation of the cardiac electrical potentials, is the most prescribed diagnostic measure in medicine and is routinely used to diagnose heart disease, to identify irregular cardiac rhythms (arrhythmias), to evaluate the effects of drugs, and to monitor surgical procedures. The magnitude, conduction, and duration of these potentials are detected by placing electrodes on the patient's skin. From the ECG tracing, the following information can be determined: (i) Heart rate; (ii) Heart rhythm; (iii) Conduction abnormalities (abnormalities in the way the electrical impulse spreads across the heart); (iv) Coronary artery disease; (v) Heart muscle abnormality etc. [Richard-a, 02]. By examining the sequence of events on the ECG, cardiologists are able to diagnose cardiac arrhythmias.

There are two main types of cardiac surveillance techniques based on ECG monitoring: HOLTER monitoring and cardiac event monitoring. HOLTER can be used to record 24hrs to 72hrs ECG signals with 1~3 leads in general. In HOLTER monitoring system, the ECG signals are processed later by dedicated software and then a diagnostic report will be created to aid cardiologists for further analysis. However, HOLTER is proved largely insufficient for a long-term prediction because the critical cardiac arrhythmias do not necessarily occur during these 72hrs [Richard-b, 02]. The R.TEST is a one lead ECG monitoring device. It may be configured by the cardiologist to record automatically cardiac arrhythmia events up to 8 days and the patient can also manually record a sequence of ECG signals when he feels uncomfortable (e.g. when he has palpitations). The recorded ECG signals may be sent to a remote PC to be later analysed either by a cardiac technician or by the physician himself through modem/Email communication [Novacor, 04]. However, one lead ECG signal is not able to localise accurately the ectopic wave and it may be corrupted by interferences such as motion artefacts. Moreover, some cardiac arrhythmias are asymptomatic and RTEST does not support real-time emergency message transmission. Some other event monitoring systems adopting similar methods, including LifeWatch [LifeWatch, 04] and CardioCall [Numed, 03] have the same inconveniences.

In order to enable the patients to accept the real-time cardiac healthcare service and to enjoy the freedom of their life, new techniques such as wireless sensor and real-time automatic ECG diagnosis (AED) must be integrated into the traditional cardiac monitoring system. Some of wireless ECG monitoring systems are introduced briefly. HP Agilent telemetry system is expensive and is generally fit for multi-patient hospital-use application [Agilent, 00]. In this system, patients must stay in hospital for cardiac surveillance; therefore the nursing fees are rather high.

Braecklein *et al* [Braecklein, 05] implement a tele-cardiological monitoring system in which the ECG signals are collected and analyzed by a wireless ECG sensor. The detected cardiac events are automatically transmitted to the local base station. From the base station the recorded ECG signal is sent via a modem and a point-to-point connection over the telephone line to an internet-based electronic health record (EHR) where the ECG and the event marker are stored. The authorized rescue dispatchers, physicians or other qualified persons are allowed to have access to the EHR to read the patient file. This system adopts the same architecture as ours. It provides one lead ECG signal with 500Hz sampling frequency and supports only one operation mode: real-time transmission of *ECG signal sequence.*

A new Australian-made mobile phone-based medical diagnostic system named ‘LifeMedic’ has been used to give medical services to the survivors in the tsunami-devastated region of Banda Aceh, Indonesia, at the beginning of January 2005 [Smart, 05]. Using LifeMedic, developed by a Brisbane-based company, patient care can be delivered in the hospital or at any remote location through mobile camera phones. The patients’ information, i.e. signal and image, are originated respectively from medical-sensors (ECG electrodes) and from digital camera, and then transmitted to a remote information centre via mobile phone over satellite communication systems, so that physicians can send medical records and pictures of wounds back to Australia for an instant diagnosis.

Some other wireless monitoring systems, such as the ones described in papers by [Karlsson, 05], [Paksuniemi, 05] and [Goh, 05], have similar architectures and functions in the cardiac monitoring applications. In the papers of [Zhou-a, 05] and [Zhou-b, 05], the author introduces the contributions of his previous research and presents different aspects of his monitoring system. The paper [Zhou-a, 05] presents the system architecture and different operation modes. The paper [Zhou-b, 05] focuses on the network communication techniques of remote surveillance platform dedicated to real-time and reliable cardiac monitoring application.

This paper gives an overview of our cardiac monitoring system, summarizes previous and ongoing works, and specifies some interesting technical details. The paper is organized as follows. In section 3, this paper gives a brief introduction about system architecture. Section 4 presents different developed techniques: embedded micro-kernel in section 4.1; real-time automatic ECG diagnosis algorithm in section 4.2; reliable communication platform in section 4.3. Finally in section 5, the performance evaluation of this system, the conclusion and the ongoing work are presented.

3 System Architecture

Our objective is to develop a system adapted to telemedicine applications, especially to real-time cardiac arrhythmias tele-assistance and monitoring. This system is generally composed of 4 main configurable elements: wireless ECG sensor, local access unit, remote centre server and remote surveillance terminal.

This system supports 4 operation modes to satisfy the different application requirements. Each mode has a unique message format, i.e., real-time monitoring and diagnosis based on *continuous ECG signals*, cardiac arrhythmia event report including *ECG signals sequence*, *textual emergency message* or diagnostic *report email.*

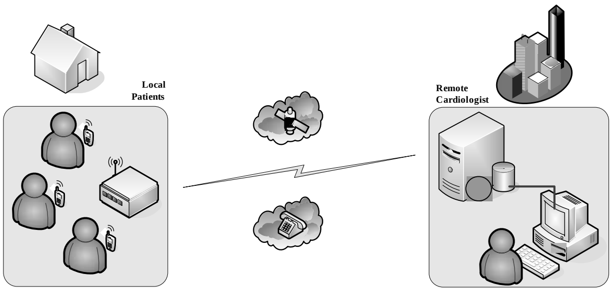
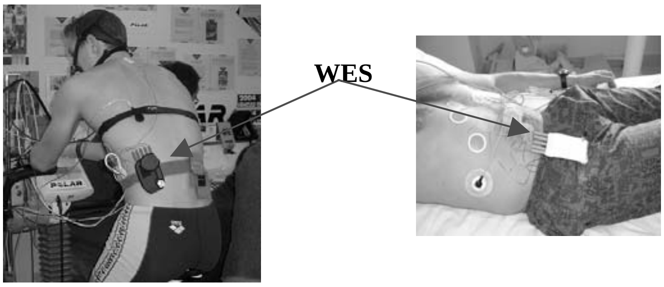


Figure 1: Real-time cardiac arrhythmias tele-assistance and monitoring system

3.1 Wireless ECG Sensor: WES

A low cost, low energy consuming and compact WES prototype responding to the last AHA (American Heart Association) recommendations [Bailey, 90] is implemented. The WES prototype (Fig. 2) is a real-time wireless embedded portable sensor (size=70*100mm) based on the Texas Instruments ultra low power micro-controller MSP430 [Texas, 00]. The technical features of WES are: (i) Gain: 1000; (ii) CMMR(min): 120dB; (iii) Bandwidth: 0.05Hz to 125Hz; (iv) Programmable sampling frequency superior to 500Hz; (v) Analogue to digital converter: 12 bits; (vi) Leakage current: 10µA.

The WES enables to capture in real-time 4 leads ECG signals sampled at 500Hz. The signals are sent simultaneously to the local server over a wireless medium such as WiFi and/or Bluetooth and/or other radio communication. In off-line mode, ECG signals are stored into a Multimedia flash memory card (MMC). The duration of the ECG records depends on the capacity of the MMC, the sampling frequency and the number of ECG leads. The last two parameters may be configured.



(a) (b)

Figure 2: Wireless ECG Sensor adopted for the athletes (a) and patients (b)

3.2 Local Access Unit: LAU

The local access unit, replacing a standard computer, is dedicated to data exchanges between WES nodes and a remote system. It provides at least two types of network access services: a local wireless connection with WES via local wireless mediums, and a remote network connection with the remote system via fixed network connections (LAN, PSTN,) or wide wireless mediums (satellite, UMTS,). In addition, the patients' video information is optional and may be used to confirm emergency alarm or to assist online diagnosis. A "webcam" can be installed in the LAU to capture patients' images.

Current LAU prototype is implemented by using National Semiconductor microprocessor CP3KBT. The embedded basic technologies such as distributed real-time fault tolerant micro kernel [DeVaulx, 02][Zhou, 02], dedicated hardware and firmware [Gineste, 02] and real-time TCP/IP protocol stack [Palau, 02][Zhou, 02] are implemented into LAU. The modular architecture of LAU is shown in Fig.3. In fact, a mobile camera phone can also be configured as a LAU element.

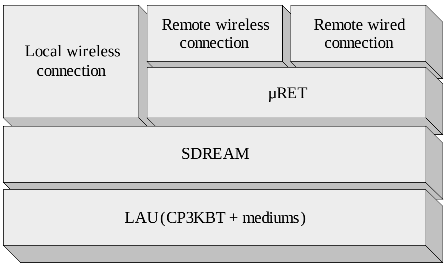


Figure 3: Local Access Unit modular architecture

3.3 Remote Centre Server: RCS

The remote centre server provides the network connection and web-based patient management service. It consists of multi-function modules: network access system (PPP/WAP) and Web-based patient database system. The network access system may be a PPP server that supports modem connection over public switch telephone network (PSTN) or a WAP server that supports seamless wireless network connection over mobile communication network. A background communication system is installed in RCS to ensure reliable real-time data transmission. The patient database server stores patient information, including ECG signal sequences with the format of WFDB [PhysioNet, 03], diagnostic reports, medical history records, images, and private profiles/account information, etc. The authorized users, including patients, and cardiologists are allowed to access the web-based database system.

3.4 Remote Surveillance Terminal: RST

The RST provides a visualization surveillance and diagnosis platform that enables to display continuous ECG signal sequences and patient images, to respond to alarm messages, and to support real-time or on-line diagnosis. Cardiologists can define operation modes and compile diagnostic reports by reviewing patients' records after logon into the web-based database system.

In case of LAU, RCS and RST are deployed in the same area such as in a department of hospital having local area network infrastructure or the application having few patients and one cardiologist, remote surveillance terminal can replace RCS and connect to LAU directly.

4 Technological Overview

The main technical challenges of this cardiac monitoring system include three main aspects: (i) Real-time automatic ECG diagnostic (AED) algorithm; (ii) Embedded real-time multi-task operating system; (iii) Real-time reliable telemedicine communication protocol. This section specifies these technical details.

4.1 Automatic ECG Diagnosis Technique

Most of traditional AED algorithms such as FFT analysis [Lin, 88], wavelet analysis [Swerdlow, 02], CWA (correlation waveform analysis) [Jenkins, 96], chaotic modeling [Cohen, 97] and neural network [Nugent, 02], generally consume huge resources and also do not meet real-time low-resource applications [Zhou, 04]. This subsection presents a real-time AED algorithm dedicated to a low-resource system. It consists of three modules (see Fig.4.).

4.1.1 Signal Preprocessing

Due to the non-stationary and easily disturbed features of the ambulatory signals, the WES acquisitions must be de-noised before making detection. Most of interferences, such as baseline drift, electrical noise and muscle tremor, can be effectively eliminated or reduced by selecting accurate filters. Some other interference such as motion artifacts must be handled in two other modules.

The signal preprocessing method adopted in this system is rather simple and efficient. It includes two groups of filters: the adaptive differentiator (adaptive filter & differentiator), where the output signal is named *AD*(t) and the de-noised amplifier (0.1~40Hz band-pass filter, 50/60Hz notch filter and linear amplifier), where the output signal is named *RC*(t). *AD*(t) is used in the QRS detection module to locate QRS complexes, and *RC*(t) is adopted in the rhythm classification module to interpret cardiac arrhythmias.

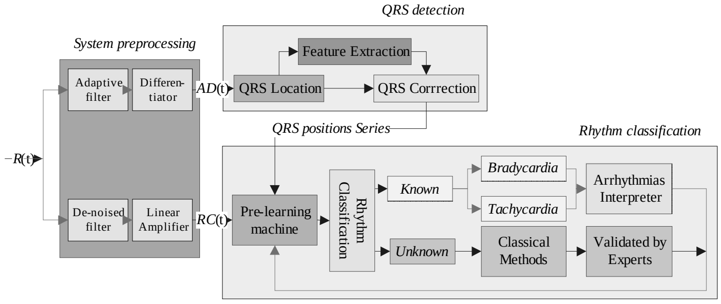


Figure 4: Bloc diagram of real-time AED algorithm

4.1.2 QRS Detection

The ECG signals can be classified into two categories according to their features: statistical and morphological features. The statistical feature is the heart rate or the RR interval. The morphological features consist of five components: R peaks, two slopes, the duration and the absolute surface of a QRS complex (Fig. 5). The basic idea of the QRS detection algorithm is to detect QRS complexes in the *AD*(t) series by adopting the geometrical method to locate the QRS positions and to extract the morphological features.

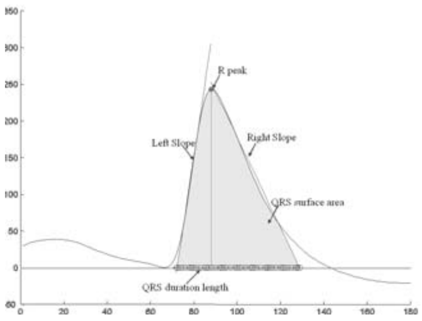


Figure 5: Morphological Features of QRS complex

The QRS detection consists of three phases: QRS location, feature extraction and QRS correction. The QRS location procedure detects QRS complexes in each diagnosis segment window (DSW). Each DSW has five seconds length. It adopts the self-adaptive threshold (SAT) method to estimate R peaks and to evaluate the optimum thresholds of each DSW. An adaptive and self-corrected procedure named state transition recognition (STR) is used to automatically track the changes of waves, to correct error detection and to identify QRS complexes. The feature extraction procedure adopts a geometric modeling method to construct the complex model and to estimate the morphological features. The QRS correction procedure adopts a two-level error correction mechanism to verify the detected QRS complexes, which is based on the features comparison, the contextual correlation analysis and the multi-fusion technique.

4.1.3 Rhythm Classification

The rhythm classification algorithm adopts the methods of the expert system associated with the confidence intervals. It includes three main steps: a pre-learning machine, a rhythm classifier and a cardiac arrhythmias interpreter. Based on the experiential rules of cardiologists and the results of the training procedure, the pre-learning machine set up the quantitative diagnostic rules for each lead ECG signals of the patient. The rhythm classifier classifies each detected heart rhythm into one of two catalogues: known or unknown rhythm. The known rhythms will be further classified into two types according to the heart rate: sinus or ventricular rhythm. For unknown rhythms, some traditional methods and experts' experiences will be adopted to classify the rhythm and the classification results will be confirmed by cardiologists. In terms of the rhythm types and the diagnostic rules, the cardiac arrhythmias interpreter is called to diagnose cardiac arrhythmias according to the symptoms of heart diseases. The diagnostic results will be fed back to the pre-learning machine to correct the diagnostic rules.

4.1.4 Performance Evaluation

The performance evaluations of QRS detection algorithm and rhythm classification algorithm have been done respectively in MIT-BIH arrhythmias database [Moody, 90] and clinical STAR database (CSD) records.

The overall results of the detection algorithm have 99.37% sensitivity and 99.68% specificity on MIT-BIH database, 99.67% sensitivity and 99.74% specificity on CSD database. This detection algorithm is a real-time algorithm since it has minimal beat detection latency. It is based on geometric features to model QRS complex, rather than on mathematical approaches from the traditional theory of signal analysis. Thus, this algorithm has low computational consumption and a fast detection capability.

The overall results of the rhythm classification algorithm have 90.90% sensitivity and 95.50% specificity on MIT-BIH database, 95.6% sensitivity, and 99.5% specificity on CSD records. Since the extracted features are the time-domain characteristics of QRS complex, the classification algorithm can directly adopt the experiences of cardiologists. Therefore it reduces the complexity of rules training and improves the accuracy of classification. Moreover our algorithm is able to identify more various cardiac arrhythmias than most of the other ones.

4.2 Dedicated Embedded System

In comparison with most of embedded devices, wearable wireless sensor has more resource constraints (CPU, memory, energy consumption etc.) and must have a wireless communication capability. Therefore most of popular embedded Real-Time Operating Systems (RTOS) cannot be ported directly into a wireless sensor device [DeVaulx, 02][Zhou, 04]. In addition, WSN applications often contain real-time concurrent behaviors (e.g. simultaneously data acquiring, processing and transmitting). The well-known WSN OS: TinyOS [Maurer, 04] is a natural single-tasking-model event-driven system, which can not support a large number of real-time interrupt tasks and can not provide a network connection capacity with traditional networks. Hence, a WSN OS should be an embedded RTOS that can support real-time multi-task operations and can be tuned to strict constrained resources.

SDREAM [Zhou, 02] is a true real-time multi-task micro-kernel dedicated to resource constrained wireless devices. It has been designed to run on a general purpose architecture where a single CPU is shared between application and system processing. SDREAM provides a highly efficient communication mechanism and a fine-grained concurrency mechanism to real-time applications. The Kernel Modeling Language (KML) is a *meta* language and it is used to define and to describe the abstract manners of system primitives and operations. In SDREAM, tasks are classified into two categories: periodic and priority. A periodic task has the highest priority level and is responsible for capturing sensor signals or actuating control signals; a priority task has various priority levels and it is suitable for time-constraint applications. A two-level task scheduling policy scheme, named “priority-based preemptive scheduling”, is adopted for electing a task. SDREAM is a tuple-based message-driven system. The tuple concept of the parallel programming LINDA is utilized for the inter-task communication and task synchronization. A shared data exchange space, named “tuple space”, consists of a set of tuples each identified by a unique ID: key. The interrupt handling mechanism of SDREAM is small and efficient; it has very short and determinate latencies to external events.

SDREAM has a flexible hardware abstraction capability; it can be easily ported on different WSN platforms and tiny embedded devices. Until now, SDREAM has been ported into three hardware platforms: TMS320C5410, MSP430F149 and CP3KBT. The minimal SDREAM version consumes only 5Kbytes memory. The optional low-power operation mode enables an application of SDREAM (500Hz four-channel data sampling and real-time wireless connection) to run more than 120hrs on a wireless sensor (MSP430F149) with a battery of 700mAH and a supply voltage of 3V. The evaluation results of the execution times of system primitives and system functions, task switch latencies, and interrupt latencies indicate that the SDREAM is deterministic and predictable RTOS.

SDREAM integrates the advantages of conventional RTOSs and TinyOS. In comparison with the popular RTOSs, SDREAM consumes lesser resources and has better interrupt latencies. The execution time of system primitives and system functions are deterministic and predictable. Hence, it can be ported into tiny resource embedded devices, especially wireless sensor network node. On the other hand, SDREAM is a true real-time multi-task system. It has a better scalability and flexibility for different hardware platforms and various applications requirements than tiny OS. SDREAM can run on the platforms ranging from tiny resource devices to complex distributed systems and can support applications ranging from simple single tasks to real-time multi-tasks.

4.3 Telemedicine Communication Protocol

In order to support a real-time data transmission, the UDP protocol is adopted in this system to transmit ECG signals because UDP has more rapid data exchange than TCP. Since the UDP protocol does not offer a guaranteed datagram delivery service, a reliable data transmission mechanism must be implemented in the system application layer.

Because the bandwidth of the network communication system is fluctuated and influenced by network traffics and some interference factors [Partridge, 93], an application layer communication protocol dedicated to this cardiac monitoring system has been implemented to ensure real-time reliable data transmission service.

4.3.1 System Data Frame

A frame is defined as a transfer data unit between remote peers and local peers in the system. Frames are used to establish/terminate connections, to deliver data (ECG signals or images), and to configure operation modes or other system parameters. Each frame consists of two parts, a frame header followed by data. Fig. 6 shows the frame format.

The type field identifies the system frame type. Three frame types are defined: a value of 0x01 indicates a system control frame, a value of 0x02 indicates an ECG signal frame, and a value of 0x03 indicates an image frame. Each type has a unique system priority identified by the type value (1 to 3, from high to low).

Fig.6 (a) shows the format of an ECG signal frame. Each ECG frame has a unique identifier specified by the sequence number. Every time the local server sends an ECG frame, the sequence number increments automatically by one. Basing upon this value, the system platform calculates the surveillance time of cardiac monitoring. The value of signal number field indicates the channel number of ECG signals (default value: 4). The value of QRS number fields represents the number of QRS complexes detected by the AED algorithm in the ECG frame. The default sampling frequency of WES is 500 Hz, which is identified in the sampling frequency field. This value is alterable by the divided frequency operation. Because the signal compression algorithm will change the size of original ECG frame, this frequency value can be used to decide the length of the uncompressed original frame in the remote peer.

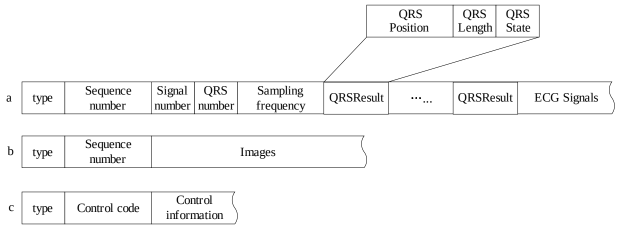


Figure 6: System Frame Format

The following fields of the ECG frame store the diagnostic results of the AED algorithm. It is a QRS structure queue, where the QRS member number is indicated in the QRS number field. Each QRS member named *QRSResult* consists of three elements: QRS position, QRS length and QRS state. The QRS position indicates the onset position of a QRS complex in the uncompressed ECG frame. The heart rate of each beat can be calculated according to the positions of two consecutive QRS. The QRS length represents the time interval of a QRS. The QRS state shows the type of heart rhythm and its related heart status classified by the AED algorithm. The ECG signals field stores the compressed ECG signals. In this protocol, each ECG frame contains 5s of ECG signals.

Fig.6 (b) shows the format of the image frame. The Sequence number field is unused in the image frame. The image field contains an image with the *jpeg* format. Fig.6 (c) shows the format of the system control information frame. The value of control code field indicates the type of control code. The related control information is stored in the following control information field.

4.3.2 System Communication Mechanisms

Three kinds of UDP connections are established in the protocol communication system. They are responsible for the system control (`udp_CMD`), the ECG signals transmission (`udp_SIG`) and the images transmission (`udp_IMG`).

4.3.2.1 System Control

The control frames are responsible for system remote configurations, the patient online/offline notifications, and the ECG frames retransmission management. The control frame is transferred via the `udp_CMD` connection. The system protocol defines 9 types of control frames (Table 1):

REQ_Connect	*ACK_Connect*
REQ_Terminate	*ACK_Terminate*
REQ_Configure	*ACK_Configure*
REQ_Restra	*ACK_5Frames*
	ACK_Image

Table 1: System Control Frame Type

The control frames with the code of REQ_Connect and ACK_Connect are responsible for the connection establishment between patients and cardiologists. The control frames with the code of REQ_Terminate and ACK_Terminate are responsible for the connection termination. Both patients and cardiologists are authorised to open/close a connection. The control frames with the code of REQ_Configure and ACK_Configure are responsible for the system configuration. Currently, the protocol provides the configurations of the operation mode and the sampling frequency. The other control frames with the code of REQ_Restra, ACK_5Frames and ACK_Image will be introduced in the following subsections.

4.3.2.2 Signals Retransmission Mechanism

The system protocol guarantees a reliable ECG signals delivery service by adopting a signal retransmission mechanism. Two ECG frame queues are defined respectively for the LAU (Hold_Queue) and the RCS (Wait_Queue). The default size of the two queues is five frames. The retransmission mechanism is described in Fig.7.

When an ECG frame with the sequence number *k* is lost during network transmission, the RCS sends a retransmission requirement frame with a control code of REQ_Restra and the LAU responses to this requirement by re-transmitting the ECG frame *k*. When five consecutive ECG frames are received in the RCS, a control frames containing the code of ACK_5Frames will be sent to the LAU to inform the release of the remainder ECG frames in Hold_Queue.

```
If  (an ECG frame is recieved)
    If (Seq_cur == Seq_exp)
        Insert current frame to wait_queue; The position of current
        frame in wait_queue is decided by its Seq_cur;
        Seq_exp++;
    else if (Seq_cur < Seq_exp)
        drop it;
        Send Control Frame REQ_Restra to the local server;
    else if (Seq_cur > Seq_exp)
        Add current frame to the tail of wait_queue;
    end

    if (continuous Five frame is received)
        Send Control Frame ACK_5Frames to the local server;
    end
end
```

```
If (ACK_5Frames frame is received)
    Release the ECG frames whose Seq_fra <= Seq_ack from the
    hold_queue;
else if (REQ_Restra frame is received )
    Retransmit an ECG frame of Seq_req to the remote surveillance
    server;
    Release the ECG frames whose Seq_fra < Seq_req from the
    hold_queue;
end

if (an ECG frame is ready)
    Send an ECG frame of Seq_cur to remote surveillance
    server;
    Seq_cur++;
end
```

Figure 7: Signal Retransmission Mechanism: RCS Peer (left) and LAU Peer (right)

4.3.2.3 Data Competition Mechanism

As mentioned above, this protocol has three types of data frames. Each kind of data frame has a unique transmission priority. The system control frame has the highest priority. Furthermore, since the ECG signals are more important than the images data for the diagnoses of cardiologists, the ECG frame has a higher priority than the image frame. In order to guarantee a real-time ECG signal transmission service, a data competition mechanism is implemented in this protocol, described in Fig.8.

When the queue length of Wait_Queue is equal or greater than five, it means that at least 25 seconds of ECG signals are stored in the RCS. Hence, it is acceptable to allow the LAU to transmit images. Whereas, when the queue length of Wait_Queue is smaller than five, it means that the network speed begins to fluctuate and the network quality is lowered; hence the system will stop the image transmission so as to reduce the network traffics.

```
If  (an Image frame is received)
    If (the length of wait_queue >= 5)    //25 seconds delays
        Send a Control frame ACK_Image to  the local server;
        Set the Image_Enable = TRUE;
    else
        Set the Image_Enable = FALSE;
    end
end

if  ( an ECG frame is received)
    If (the length of wait_queue > 5 && Image_Enable == FALSE )
        Send a Control frame ACK_Image to  the local server;
        Set the Image_Enable = TRUE;
    end
end
```

```
If  (Image_Enable == TRUE)
    Send an Image frame to  the remote surveillance server;
    Set the Image_Enable = FALSE;
end

if  ( a Control frame ACK_Image is received)
    Set the Image_Enable = TRUE;
end
```

Figure 8: System Competition Mechanism: RCS Peer (left) and LAU Peer (right)

5 Conclusion and Ongoing Work

Currently, the cardiac monitoring system has been evaluated on 30 patients at the CHRU of Gabriel Montpied hospital (Clermont-Ferrand, France). Most of them have acute cardiac arrhythmia disturbances. For each patient, the monitoring duration is more than 30mn. Because the patients and the cardiologists are located at the same area (at hospital), the 4-lead ECG signals are sent directly to the remote surveillance terminal (RST) in real-time with *continuous ECG signals* operation mode. In this system, the cardiac arrhythmia events can be detected and sent in real-time to the cardiologists. Note that, during the evaluation, each patient is also equipped with the HP telemetry device. The results obtained by our system and by HP telemetry system are compared. Due to the higher sampling frequency, the ECG signals of our system are better than the HP telemetry system ones. Concerning the cardiac arrhythmia detection, the two systems have similar results. For real-time ambulatory continuous cardiac arrhythmia detection, we obtained the following results: the average detection rate of VT (ventricular tachycardia) and ESV (extrasystolic ventricular) is about 95% [Zhou, 04]. The evaluation results prove that this system meets the requirements of real-time cardiac monitoring and diagnosing application.

The system has also been utilized to evaluate the athletes' cardiac status during physical exercises. The obtained results show that this system still provides high quality ECG signals and accurate QRS detection.

In order to improve this system, we should develop the following techniques: (i) Embedded RTOS (i.e. SDREAM) has to adopt a full "modularity" design fashion. The system primitives and tasks of SDREAM will be defined as a set of actions. Thus, it may be configured according to different applications. (ii) AED algorithm has been ported into the local access unit and the remote centre server, but it can be integrated as an ECG diagnostic chip. We are working on the implementation of an Intelligent Wireless ECG Sensor (IWES) by integrating the algorithm into a VLSI chip. This chip is currently under evaluation and test on an ALTERA FPGA board.

Acknowledgments

We gracefully acknowledge all the anonymous reviewers for their valuable advices and suggestions.

References

[Agilent, 00]Agilent Technologies: "Porbe: Exploring medical technology with agilent technologies", Product Document, Agilent Tchnologies, Fall, 2000.

[Bailey, 90]J.J. Bailey, *et al*: "Recommendations for standardization and Specifications in automated electrocardiography: Bandwidth and digital signal processing", Special report Circulation, 81(2), pp. 730-739, Feb. 1990.

[Braecklein, 05]M. Braecklein, I. Tchoudovski, C. Moor, K. Egorouchkina, L.P. Pang and A. Bolz: "Wireless Telecardiological Monitoring System for the Homecare Area", Proceedings of EMBC'05, paper 587, Shanghai, September, 2005.

[Cohen, 97]M. Cohen, D. Hudson and P. Deedwania, "Applying continuous chaotic modeling to cardiac signal analysis", IEEE Eng Med Biol, 15(5): 97-102, 1997.

[DeVaulx, 02]C. De Vaulx, K.M. Hou, DREAM: “un micro noyau réparti, temps réel orienté pour la tolérance aux fautes”, revue Informatique et santé, télémédecine et e-santé, vol 13, pp.63-69, 2002.

[Ellenbogan, 92]K.A. Ellenbogan: “Cardiac Pacing”, Chapter 1, pp.1-10, Blackwell Scientific Publications, 1992.

[Gineste, 02]L. Gineste: “Plate-forme de suivi à distance d’arythmie cardiaques”, Rapport de DEA CSTI, Université Blaise Pascal Clermont-Ferrand II France, 2002.

[Goh, 05]K. W. Goh, J. Lavanya, Y. Kim, E. K. Tan and C. B. Soh: “A PDA-based ECG based beat detector for home cardiac care”, Proceedings of EMBC’05, paper 1238, Shanghai, September, 2005.

[IME, 02]Internet Medical Education, Inc: “Sudden death and how to prevent it”, Commentary Document from Internet Medical Education, Inc., 2002.

[Jenkins, 96]J.M. Jenkins and S.A. Caswell: “Detection Algorithms in Implantable Cardioverter Defibrillator”, Proceeding of the IEEE, vol. 84, No.3, pp. 428-445, Mar. 1996.

[Karlsson, 05]M. Karlsson, R. Forsgren, E. Eriksson, U. Edström, T. Bäcklund, J.S. Karlsson and U. Wiklund: “Wireless Telecardiological Monitoring System for the Homecare Area”, Proceedings of EMBC’05, paper 600, Shanghai, September, 2005.

[LifeWatch, 04]LifeWatch Inc.: “LifeWatch Watch: 30-day Cardiac Event Monitoring”, Product Document, http://www.lifewatchinc.com, 2004.

[Lin, 88]D. Lin, L. DiCarlo and J. Jenkins,“Identification of ventricular tachycardia using intracavitary ventricular electrograms: Analysis of time and frequency domain patterns” , Pacing Clin Electrophysiol, 11:1592-1606, 1988.

[Maurer, 04]W. Maurer, “The Scientist and Engineer’s Guide to TinyOS Programming”, http://ttdp.org/tpg/html, 2004.

[Moody, 90]G.B. Moody and R.G. Mark: “The MIT-BIH Arrhythmia Database on CD-ROM and software for use with it”, Computers in Cardiology, 17:185-188, 1990.

[Novacor, 04]Novacor-Technologies: “R.TEST evolution 3 presentation”, Product Document, http://www.novacor.com/english/cadres.htm, 2004.

[Nugent, 02]C.D Nugent, J.A Lopez, A.E Smith and N.D Black, “Prediction models in the design of neural network based ECG classifiers: A neural network and genetic programming approach”, BMC Medical Informatics and Decision Making, 2:1, Jan. 2002.

[Numed, 03] Numed Holdings Ltd.: “CadiaCall Event Monitoring System”, Product Document, http://www.numed.co.uk/cardiocall.html, 2003.

[Paksuniemi, 05]M. Paksuniemi, H. Sorvoja, E. Alasaarela, R. Myllylä: “Wireless sensor and data transmission needs and technologies for patient monitoring in the operating room and intensive care unit”, Proceedings of EMBC’05, paper 786, Shanghai, September, 2005.

[Palau, 02]P. Palau, K.M. Hou and J. Ponsonnaille: “TelmedTCP: Protocole TCP/IP temps réel dédié à la télémédecine”, revue Informatique et santé, Télémédecine et e-santé, Springer-Verlag France, vol. 13, pp. 53-60, 2002.

[Partridge, 93]C. Partridge: “The End of Simple Traffic Models (Editor’s Note)”, IEEE Network, vol. 7, No. 5, page3-3, Sep. 1993.

[PhysioNet, 03]PhysioNet: “The WFDB Software Package Software for viewing, analyzing, and creating recordings of physiologic signals”, PhysioToolkit manuals, 2003.

[Richard-a, 02]N. Richard and M.D. Fogoros: “The Electrocardiogram (ECG)”, http://heartdisease.about.com, 2002.

[Richard-b, 02]N. Richard and M.D. Fogoros: “HOLTER Monitors and Event Recorders”, http://heartdisease.about.com, 2002.

[Smart, 05]Smart Queensland publications: “System a success in tsunami aid effort”, Catalyst - Issue 13, March 2005.

[Swerdlow, 02]C.D. Swerdlow, *et al*: “Discrimination of Ventricular Tachycardia from Supraventricular Tachycardia by a Download Wavelet-Transform Morphology Algorithm: A Paradigm for Development of Implantable Cardioverter Defibrillator Detection Algorithm”, Journal of Cardiovascular Electrophysiology, vol. 13, No. 5, May 2002.

[Texas, 00]Texas-Instruments: “MSP430x13x, MSP430x14x signal microcontroller”, pp.1-67, Jul.2000.

[WHO, 03]World Health Organization: “The premise program: Prevention of REcurrences of Myocardial Infarction and StrokE Study”, Country projects, 2003.

[Zhou, 02]H.Y. Zhou, *et al*: “A Configurable Micro Network Kernel dedicated to real-time distributed embedded network sensor: Telemedicine application”, 6th international conference on signal processing proceedings, Beijing, pp. 1748-1752, Aug. 26-30, 2002.

[Zhou, 04]H.Y. Zhou: “Wireless Sensor Networks Dedicated to Remote Continuous Real Time Cardiac Arrhythmias Detection and Diagnosis”, PhD. thesis, UBP Clermont-Ferrand, 2004.

[Zhou-a, 05]H.Y.Zhou *et al*: “Real-time Cardiac Arrhythmia Tele-Assistance and Monitoring Platform: RECATA”, Proceedings of ICOST’05 : From Smart Homes to Smart Care, Assistive Technology Research Series V15, IOS Press, pp.99~106, July, 2005.

[Zhou-b, 05]H.Y. Zhou, K.M. Hou, J. Ponsonnaille, L. Gineste and C. de Vaulx, “Real-time Arrhythmias Tele-Assistance and Monitoring Platform: RECAD”, Proceedings of EMBC’05, paper 882, Shanghai, September, 2005.