ECG CLASSIFICATION AND ANALYSIS IN A ZIGBEE WIRELESS SENSOR NETWORK

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Abstract: Wireless technology has become ubiquitous in our daily lives. From 802.11 to Bluetooth we have become familiar with new technologies and expectations are rife as to its potential. The medical world is potentially lucrative for the use of such technology. The ability to improve patient comfort, monitor patients remotely and increase device mobility should all contribute handsomely to patient life quality. It also offers the unique opportunity to monitor ambulatory patients in a real-time environment. Outlined is an approach to integrate an Electrocardiogram (ECG) classifier into an overall wireless patient monitoring system enabling real-time classification and analysis of ECG data. Our research has shown that it is possible to use the open source classifier (Hamilton, 2002) in a wireless sensor network for beat detection and arrhythmia classification. We have tested the classifier with up to 80 simulated sensors proving that its lightweight implementation enables it to cope perfectly with only minor modifications needed. It was found that the addition of multiples of sensors produced on average 0.01% performance degradation.

1 INTRODUCTION

Ambulatory patient monitoring is crucial to post operative care in many modern day hospitals. In many cases the onset of cardiac arrhythmias can signal a more serious underlying condition. Traditionally holter monitors were used to classify infrequently occurring arrhythmias and cardiac abnormalities in an ambulatory environment. Holter recordings normally comprise of 24-48 hours of ECG data, with post-classification occurring after the recording has completed. Potentially life threatening conditions and arrhythmias would only be detected in retrospect. With this in mind it was decided that, classifying ECG data in real-time, raising alarms as problems arose, would be extremely beneficial for both patient and practitioner.

Classifying arrhythmia's in a real-time ambulatory environment poses challenges with respect to redundancy, reliability and resource constraints. A beat detector and classifier was needed that could operate effectively under these limitations. The Open Source classifier written by Patrick Hamilton and provided by EP Limited was chosen as a result of this. With QRS detection sensitivities close to 99.8% on MIT/BIH and AHA databases coupled with classification positive predictivities of 96.48% and 97.83% on MIT and AHA databases respectively (Hamilton, 2002), it's accuracy is excellent. Its QRS detector was originally developed by Pan and Tompkins and designed to operate in real-time. All the processing is done with integer arithmetic so that the algorithm can operate in real-time without requiring excessive computing power (Pan, 1985).

This paper aims to demonstrate an approach to ECG classification in a wireless sensor network. We show how the Open Source beat detector and arrhythmia classifier in a Zigbee enabled wireless sensor network copes easily with the demands of real-time classification.

ECG data classification is part of a wider project called VISOR (Enhanced **VI**tal **S**ign **O**bservation and **R**ecording). VISOR is an overall wireless patient monitoring system that monitors respiratory, pulse oximetry (SP02), and ECG data in real-time, raising alarms as problems arise. The VISOR project has been in existence for three years.

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2 RELATED WORK

Extensive research has been carried out in the application of wireless sensor networks to the medical domain. Projects such as Harvard's "CodeBlue" project (Malan) have proven the validity of transmitting ECG data over Zigbee, but they are not classifying the data in real-time. Others such as the "WISE" (Jovanov, 2001) bio-medical sensors tend to focus more on data acquisition rather than data analysis. Fensli propose using sensor networks coupled with limited arrhythmia classification in the home (Fensli et al, 2005). ECG is transmitted from the home via a GPRS/GSM band to the hospital for analysis by consultants. In contrast our system aims to detect a wide range of cardiac arrhythmias, focusing on potentially serious abnormalities with the view to early diagnosis. Our system will also display other patient vitals.

While commercially available products such as the G.E. Apex Pro Telemetry System (GE Healthcare) and the LifeSync Wireless ECG system (Wireless ECG) are not using sensor networks to transmit ECG data, they are proving the commercial potential of wirelessly enabling ECG.

3 THE VISOR SYSTEM

VISOR is a Zigbee enabled patient monitoring system, consisting of multiple sensors attached to multiple patients. These sensors currently consist of ECG, SP02 and MDI (Medical Device Interface) sensors. The sensors obtain bio-data from the patient and transmit it to the server for analysis via a Zigbee module on the device. The server analyses the bio-data for eventual display on the client. A database is used to store all relevant patient demographics and bio-data for historical playback.

Data produced by the ECG sensors is sampled at 200Hz, and then passed through three second order band pass filters and the savitzky-golay (Savitzky, 1964) smoothing filter. It's then transmitted to the server for classification and analysis. The SP02 sensors transmit the heart rate and oxygen saturation levels, while the MDI sensor which is essentially a serial to wireless bridge, interfaces with existing devices in the ward to obtain patient bio-data. These devices can range from vital signs monitors to ventilators and infusion pumps. Our MDI architecture allows for the addition of new or legacy medical devices to the system increasing scalability.

3.1 Zigbee

Zigbee's suitability has already been established by others as a reliable platform for the transmission of ECG data (Lin et al, 2006). It has also been shown (Frehill, 2008) how Zigbee meets our requirements with respect to bandwidth, scalability and redundancy when handling real-time ECG data. Zigbee is based on the IEEE 802.15.4 standard (IEEE 802.15.4). Its advantages include, mesh networking, low power consumption, security and mobility (Zigbee Alliance). The Zigbee mesh networking framework provides a flexible approach to routing data in a hospital environment where any node can be used to route the ECG data. Zigbee's low power consumption enables ECG sensors to have smaller, lighter batteries that run for longer. This also offers relatively low device maintenance for nurses and hospital care workers, where sensors need only be re-charged once every 7 days.

3.2 Custom GUI Client

The central server relays relevant data to all subscribed clients. Our client software was developed using the .NET framework, enabling the software to operate on any windows based device. Subscribed clients can range from handheld PDA's/laptops to PC's. The client contains all relevant patient demographics, displaying details of attached devices and patient vitals. A patient's ventilator data, ECG "Figure 1" and plethysmogram "Figure 2" graphs are rendered for the user to scrutinize.

If an arrhythmia or alarm condition is detected, the server will notify associated clients, by raising an alarm on that client. Annotation codes defined by physionet (Physiologic Signals) to label events in an ECG recording are used to identify the type of arrhythmia that occurred. If the user wishes to view a particular alarm, the ECG graph can be played back to view the detected arrhythmia. This allows critical care workers to monitor patients remotely and less frequently.

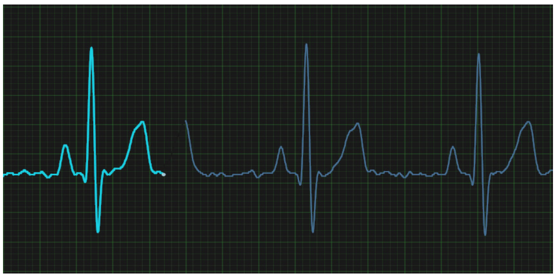

Figure 1: Client ECG Trace.

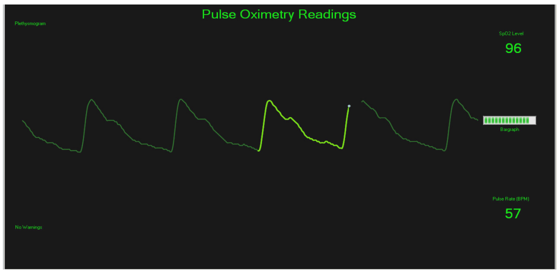

Figure 2: Client SP02 Plethysmogram.

3.3 Wireless Gateway

A PANC (Personal Area Network Coordinator) acts as a gateway transmitting data from the sensors to the analysis server as shown in “Figure 3”. The gateway is responsible for forming the network and inserting/removing wireless sensor nodes from the system.

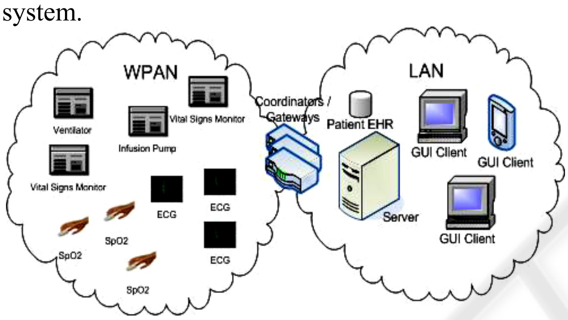

Figure 3: High Level Architecture.

3.4 Central Analysis Server

Our system classifies ECG data on a central server. Unlike other ECG wireless sensors that classify the ECG data on the device itself (Fariborzi, 2007), we feel that classifying the ECG data on the server gives us scope for scalability, allowing us to eventually analyze ECG data with multiple ECG classifiers. Combining multiple classifiers on a tiny ECG module where memory, battery life and processing power are at a premium would not be prudent. The focus of VISOR is to produce sensors that are lightweight and cost effective (Rotariu, 2006).

Once a node is powered on it begins sending status messages to the server via the gateway. When the server receives a status message from a sensor it adds that sensor to its list of active sensors, only active sensors can be associated with a patient.

Analyzing bio-data on a single central server can raise concerns regarding efficiency and scalability. The VISOR project has placed enormous emphasis on developing computationally efficient analytical modules. It has been possible as a result of this, to maintain our single analysis server architecture, all the while increasing scalability and cost effectiveness.

4 OPEN SOURCE CLASSIFIER

To facilitate the processing of live ECG data we needed a QRS detector and beat classifier that could operate in real-time. We felt that since the open source classifier’s QRS detector had originally been intended to analyse real-time ECG data, it would cope with the constraints of beat detection in this unique environment. Its lightweight classifier, implemented in C, added to its efficiency.

The QRS beat detector was ported to C by Hamilton and Tompkins (Hamilton, 1986). The beat classification rules were developed by Hamilton. The advantages of this QRS detection algorithm are that it is computationally efficient and easily modified for different samples rates (Hamilton, 2002). Our ECG sensors produce 1 lead ECG data sampled at 200Hz. The performance of the classifier has been shown to be slightly better with data sampled at 200Hz, compared to data sampled at higher rates. Its published results were based on a single channel of ECG data, similar to the data our sensors produce. Many modern day commercial classifiers work with 12 lead, 3 channel ECG data to detect arrhythmias and abnormalities. For these reasons we felt the open source classifier was the closest match in meeting our requirements for efficiency and accuracy.

4.1 Dynamic Link Layer (dll) Integration

In keeping with the existing server architecture which supports several devices, the classifier was implemented as a dll on the analysis server (Frehill, 2007). Within this framework subsequent classifiers can be added as required by loading their respective dll’s.

In order to allow for classification in a real-time environment a number of modifications have had to be made. The classifier comes with functions to analyse MIT/BIH and AHA records. It uses the WFDB library functions to read the ECG data from the records and write to annotation files. We stripped the classifier of all WFDB types, rewriting a number of functions and deleting redundant ones. The entire C program was converted into OO C++, for the purpose of instantiating instances of classifier objects. This allowed the classification of multiple sensors in real-time.

With this in place we were then able to modify and integrate George Moody's ihr.c. Instantaneous heart rate (IHR) calculates the heart rate from the reciprocals of the inter-beat intervals. This extension enabled the detection of episodes of Sinus Tachycardia/Bradycardia during normal Sinus rhythm. Once an episode has been detected an event is raised on the server that is handled on the client.

4.2 Packet Loss

A single packet loss on the network could result in the detection of an arrhythmia or unclassifiable beat due to packet size. The Zigbee software stack handles packet loss which we have proved in our laboratory environment. In addition packet sequence numbers are tracked and if a discontinuity is detected, the classifier is notified. Any arrhythmias and beats detected during this window are ignored. It would be inappropriate to call the reset method on the classifier, as normal rhythms and beat templates have already been determined and would be lost. Packet loss may occur as a result of a sensor moving out of range or if the battery is fully drained.

5 RESULTS

In the absence at the time of publication of a sufficient quantity of physical ECG sensors, it was decided to simulate the presence of multiple sensors on the system to ascertain results. We placed both the simulation software and the server software on separate P.C's with each P.C containing a Pentium 4 HT processor and 1GB of RAM. The physical ECG sensors transmit 100 bytes of data at a rate of 1 packet every 500ms, which our simulation software emulates. For the ECG data simulation we took a single record at a time, with each sensor transmitting data from the same record simultaneously. In trying to mimic a hospital environment, we simulated a mixed scenario where some patients were associated with one sensor and some with many sensors. The data was handled by the PANC and sent to the server for processing.

Four MIT/BIH arrhythmia records (100, 103, 106 and 119) were chosen to simulate the ECG data. These were selected for their disparate abnormalities. Records 106 and 119 contain a substantial amount of premature ventricular contractions (PVC) whereas 100 and 103 contain predominately normal beats. As you can see from "Table 1" the classifier had lower detection times on records that contained fewer PVC's (100, 103).
The performance differential on records 106 and 119 is largely due to the beat classification techniques involved in arrhythmia detection. It shows that detecting arrhythmias involves longer detection times, due to post classification and beat template matching.

When classifying normal beats the classifier will compare the beat to the dominant rhythm, if it's the same it's classified as normal.

Table 1: Detection Times (ms).

Record	Number of Sensors			
	20	40	60	80
100	1436.98	1437.01	1437.07	1437.14
103	1530.00	1530.01	1530.04	1530.06
106	1668.07	1668.07	1668.11	1668.25
119	1642.09	1642.20	1642.32	1642.35

To derive the beat detection average, the processing times for five hundred beats were used. From the graph "Figure 4" you will see that there is virtually no performance degradation even when tested with upwards of 100 sensors. In fact in the lab we found that performance only began to lag with 20 times that amount. Theoretically we hope to be able to classify beats from hundreds of sensors on a single server. With the advent of multi-core processors and cheaper faster RAM our server implementation will scale to meet demands.

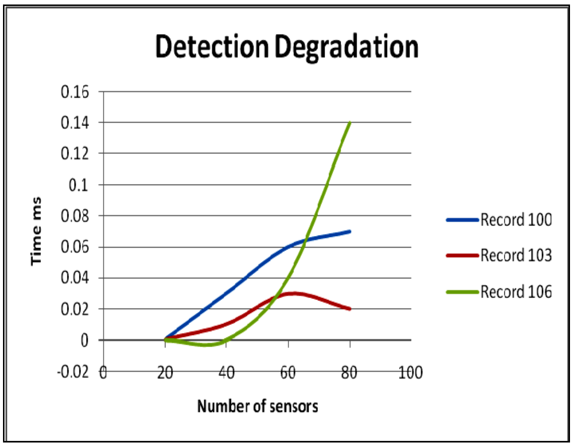

Figure 4: Detection Degradation.

6 FUTURE WORK

We are currently integrating the HeartFx 2000 arrhythmia (Heart FX 2000) classifier developed by Medata. Unlike the QRS detector in the open source classifier, the HeartFx 2000 classifier was not designed for real-time analysis. It is intended instead to be used in a post classification environment, analyzing holter recordings.

We hope to compare the performance of both of these classifiers, with respect to efficiency, accuracy and reliability while running multiple ECG sensors transmitting data simultaneously. We feel that multiple ECG classifiers would give us greater beat detection and classification redundancy in a range of disparate environments.

Using the commercial classifier as a reference we would hope to extend the open source classifier to detect new arrhythmias such as VT (Ventricular Tachycardia), VF (Ventricular Fibrillation) and Asystole. There are plans to carry out usability testing in a hospital.

7 CONCLUSIONS

It has been shown that it is possible to integrate and implement an open source ECG beat detector and arrhythmia classifier in an ambulatory patient monitoring system. Our results prove that our architecture is capable of supporting large numbers of ECG sensors simultaneously. Using Zigbee as our wireless infrastructure has enabled us to produce low cost, low power ECG sensors. We hope that, in long term patient monitoring, where accurate classification of arrhythmias is crucial, our system will prove useful.

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