A wireless ECG monitoring system for pervasive healthcare

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Abstract: This paper presents an architectural framework of a system utilising mobile technologies to enable continuous, wireless, electrocardiogram (ECG) monitoring of cardiac patients. The proposed system has the potential to improve patients' quality of life by allowing them to move around freely while undergoing continuous heart monitoring and to reduce healthcare costs associated with prolonged hospitalisation, treatment and monitoring.

Keywords: pervasive healthcare; e-health; telemedicine; wireless; electrocardiogram (ECG); cardiology; patient monitoring.

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1 Introduction

Cardiovascular disease is one of the main causes of death across the globe, including the USA (Gouaux *et al.*, 2003), and in 1999, it accounted for over 15 million (or 30% of all) deaths worldwide. In addition, several million people are disabled by cardiovascular disease (WHO, 1999). The delay between the first symptom of any cardiac ailment and the call for medical assistance has a large variation among different patients (Gouaux *et al*., 2003) and can have fatal consequences. One critical inference drawn from epidemiological data is that deployment of resources for early detection and treatment of heart disease has a higher potential of reducing fatality associated with cardiac disease than improved care after hospitalisation. Hence, new strategies are needed in order to reduce time before treatment and to capitalise on the inherently mobile nature of the field of medicine (Wen and Tan, 2005). Pervasive monitoring of patients is one possible solution. Health professionals are increasingly using mobile technologies to gain access to medical data from remote locations and pervasive healthcare technologies such as continuous cardiac monitoring represent a natural progression in this area (Medicine on the Move, 2004).

1.1 Target population

The worldwide population of adults over 65 years of age is predicted to reach 761 million by 2025 and a large majority of the aging population suffers from chronic heart diseases. Providing quality healthcare to the aging population is putting additional strain on the dwindling financial as well as human resources of the healthcare sector. The USA alone spends approximately $600 billion annually in meeting the needs of victims of chronic diseases. Hence, it is imperative for the healthcare sector to leverage technology to minimise healthcare costs. Also, the trend towards an independent lifestyle has increased the demand for personalised non-hospital based care (Tablado *et al*., 2003). The architectural framework proposed in the current research for pervasive electrocardiogram (ECG) monitoring is targeted towards older patients who suffer from chronic cardiac disease and those who are at risk of cardiac disease. The objective is to provide pervasive monitoring of these patients in an effort to detect anomalies early and provide medical intervention as and when required, thus enabling patients to live independently longer while economising the scarce human resources of the healthcare industry.

1.2 ECG

A key factor related to cardiovascular disease is the presence of acute chest pain, however this can also be caused by other medical problems and some cardiac arrests are silent. The only reliable diagnostic tool available for assessing the probability of a cardiac event is ECG. It represents the electrical activity of the heart as recorded from electrodes attached to the body of a patient and is the most frequently performed test to evaluate the level of health of patients with malfunctioning or irregular functioning of the heart (Nussbaum and Wu, 2002; Schlant *et al*., 1992; Liszka *et al*., 2004). The sensitivity and specificity of using ECG as a diagnostic tool can be greatly increased if a previous reference ECG of the patient is also available. This helps to eliminate the error caused by inter-patient variability and could allow for analysis of serial changes in ECG recordings (Gouaux *et al*., 2003). Transmitting ECG signals to the hospital in case of an emergency situation has the potential to reduce response time in infarct control or resuscitation of sudden-cardiac deaths victims (Nussbaum and Wu, 2002).

2 Related work in wireless ECG

Advances in wireless technologies have made it possible to record and transmit digital ECG signals obtained in a remote location to the computer or hand-held PDA of a healthcare professional instantly, hence reducing the time taken for evaluation and treatment (Gouaux *et al.*, 2003; Nussbaum and Wu, 2002; Khoor *et al.*, 2001; Hung and Zhang, 2003).

Work on related issues in ECG monitoring include research on 'smart health wearables' (Lymberis, 2003), interference related to telemetry devices (Gieras, 2003), Personal Digital Assistant (PDA) as a mobile gateway (Jovanov *et al.*, 2002), long-term health monitoring by wearable devices (Suzuki and Doi, 2001), a short range Bluetooth-based system for digitised ECGs (Mendoza and Tran, 2002), a wearable stethoscope (Kyu and Asada, 2002), and, real-time monitoring of patients in the home environment (Khoor *et al.*, 2001). Clothing-embedded transducers for ECG, heart rate variability, and acoustical data and wireless transmission to a central server are proposed in (Jovanov *et al.*, 2002). A requirement model for delivering alert messages is presented by Kafeza *et al.* (2004). A design approach for ECG data compression for a mobile tele-cardiology model is presented by Istepanian and Petrosian (2000) who achieved a significant compression ratio and reduction in transmission time over GSM network. Personal health monitors based on wireless Body Area Network (BAN) of intelligent sensors are proposed for stress monitoring (Jovanov *et al.*, 2003). Many portable monitors are available today such as Micropaq that allows multi-parametric information to be transmitted over wireless LANs[1] and LifeSync,[2] which uses bluetooth to move information within a hospital infrastructure. Wang and Du (2005) have discussed setting up of WLAN in a healthcare system.

Liszka *et al.* (2004) present a prototype of a system where a portable ECG monitor is used along with wireless networks to monitor arrhythmias. The system uses a fixed sampling rate of 250 and transmits a 9-byte minimum message for every measurement in 4 milliseconds. Although the paper presents many system-level issues and makes significant contributions, it suffers from many problems:

a it requires considerable bandwidth per person and will affect scalability once the number of patients increase significantly

b it is tied to using GPS for location tracking and will have limited usability in indoor environments and places where direct line of sight is not possible

c it is dependent on certain type of wireless networks such as Bluetooth and GPRS.

Unlike the current work, most of the prior researches in telemedicine have merely used PDAs as a tool to capture and send biometric data to a remote location instead of leveraging the power of PDAs to carry out computational analysis that can save costs, lower the burden on network traffic and detect anomalies earlier (Tablado *et al.*, 2003). In this paper the architecture of a scalable, wireless ECG monitoring system is presented utilising the capabilities of intelligent agents, PDAs and advanced wireless technologies to promote pervasive monitoring of cardiac patients. Scalability is achieved in the operation of the proposed system since analysis of the recorded ECG data is done by the intelligent agents housed in the patient's PDA and alerts along with the ECG data are transmitted to the healthcare centre only when an anomalous event is detected and medical attention is warranted, thereby reducing network traffic and cognitive overload of the healthcare professionals. A prioritised transmission mechanism is proposed to improve network delays. Additionally, the proposed system allows multiple technologies for location management and thus is more usable and is not tied to certain types of wireless networks. The proposed system can be implemented on WLANs, bluetooth, and *ad hoc* wireless cellular/PCS/GSM type wireless networks.

This paper describes the architecture of a wireless ECG monitoring system designed to promote ubiquitous monitoring of cardiac patients for anomalous events that could have fatal consequences if gone unnoticed. This will:

a promote early detection and treatment of cardiac diseases, hence reducing fatality due to cardiac arrests

b reduce unnecessary hospitalisation costs associated with long-term monitoring and treatment of cardiac patients

c enable patients to lead an independent lifestyle for as long as possible instead of being confined to a nursing home/hospital (Varshney, 2004).

The contributions of the research include protocols and an architectural framework of a system for continuous, wireless ECG monitoring of cardiac patients, and identification of various technical as well as non-technical challenges, solutions and future direction associated with wireless patient monitoring.

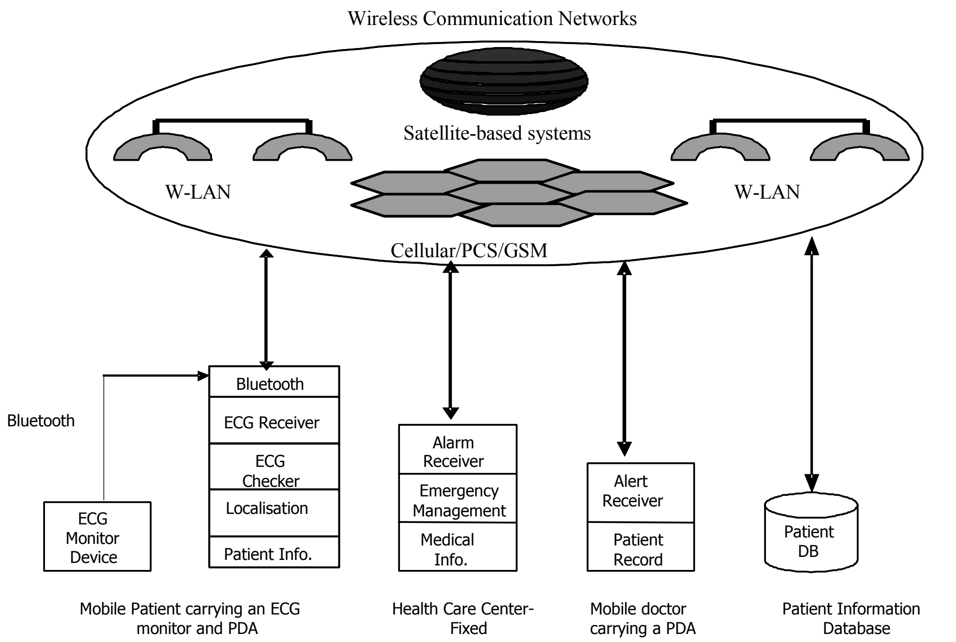
3 Architectural framework for wireless ECG monitoring system

In this section, we present an architectural framework of the proposed system (Figure 1), which consists of the following components:

- An easy-to-wear mobile ECG monitoring device, which provides one ECG record lead and consists of two electrodes that are attached to the patient's body. The ECG frequency ranges from 100 to 400 Hz and the resolution is 8–12 bits/sample. The ECG readings are communicated from the monitor to the patient's PDA via Bluetooth. The choice of Bluetooth came from the fact that it is low cost, low power and robust. Besides a number of medical sensor devices support Bluetooth communication (Liszka *et al*., 2004).
- A PDA for the patient with intelligent agents to acquire the ECG data from the monitor, perform the analysis of the recorded ECG readings and send alarm messages to the healthcare centre in case an anomaly is detected.
- A PDA for the doctor and the healthcare centre whose primary goal is to provide quick medical assistance to the cardiac patient anywhere and anytime when an anomalous condition is detected.
- The communication/information exchange between the intelligent agents in the patient's PDA, the healthcare centre and the doctor's PDA takes place via a wireless communication network. The architecture is designed in order to provide wireless coverage in both rural as well as urban areas and for indoor as well as outdoor environments likewise. The proposed architectural framework of the wireless ECG system achieves the aforementioned goal by providing access to multiple wireless networks to enhance reliability and scalability in terms of number of users, location

and application. Continuous monitoring in urban areas can be achieved by using public wide-area cellular networks combined with wireless LANs for the crowded indoor/outdoor urban areas. In rural areas where which have partial or unreliable services by wide area cellular networks, the proposed architecture supports both satellite and wireless LANs. In addition, the architecture can also provide support for *ad hoc* networks combined with infrastructure based wireless networks for those areas which have spotty coverage. The patient devices can act as routers forwarding packets till they reach a base station or an access point. Hence the patient is continuously monitored for changes in cardiac events regardless of the location within the coverage of the network.

Figure 1 Framework of the wireless ECG monitoring system with intelligent agents



The issues associated with security and privacy is salient to any healthcare application especially since Health Insurance Portability and Accountability Act (HIPAA) puts a legal sanction on transaction of patient related information. Security of patient's data transmitted over a wireless communication network is achieved in the current research by encoding the transmitted message and data in XML and encapsulating the encoded ECG in SCP-ECG format. The ID given to each patient being monitored is a random number, thus the ID by itself is not enough to identify an individual patient. However, the medical community has not developed recommendations for the appropriate compilation, use and preservation of patient's data transmitted over a wireless network (Liszka *et al.*, 2004). The issue is still open to debate whether encryption of the transmitted message should be done since decryption would waste valuable time that could be used in providing help to the patient in need. But the obvious trade-off is putting security and privacy at risk.

The proposed system analyses serial ECG recordings and detects the presence of an anomalous condition by the use of intelligent agents located in the patient's PDA. The intelligent agents use an ontology that categorises different alerts, which correspond to violations of boundary conditions as specified by the threshold ECG recordings. The ontology is represented using DAML+OIL,[3] which is based on Description Logic (DL).[4] These agents carry out a large chunk of analysis of the ECG in the PDA and send alerts only if an anomaly is detected thereby reducing traffic on the wireless networks along with economising the labour force in the healthcare sector, making the system more cost-efficient and involving the healthcare structure without delay *but* only when needed.

An Intelligent agent is a software entity that has reasoning, planning and learning capability along with the capability to communicate with other agents in order to accomplish a certain goal specified by the user. It shows autonomous behaviour and can react in a timely manner in response to certain pre-defined anomalous conditions (Nealon and Moreno, 2003). It is a mammoth task for a healthcare professional to interpret, analyse and provide error free diagnostics based on vital data stream, such as ECG readings, collected from a patient who is continuously monitored to detect anomalous conditions (Mabry *et al*., 2002). The use of intelligent agents with clear goals and relevant knowledge, as proposed in the current research, has the capability of assisting healthcare professionals in continuous patient monitoring in the form of ongoing analysis and diagnosis of large amount of complex data and alerting the health centre in case of an anomaly via multi-agent communication. This has the benefit of not only reducing the cognitive overload of healthcare professionals but also promoting timely intervention of healthcare structure as and when required.

Some of the other systems that have used intelligent agents in healthcare domain are described by Moreno and Isern (2002), Mouratidis *et al*. (2002), Mabry *et al*. (2002; 2003), and Tablado *et al*. (2003). Mabry *et al*. (2002) presents the notion of Intelligent Monitoring Agents (IM-Agents) in the healthcare setting. The paper reports on the motivation and challenges associated with IM-Agents and provide description of a fundamental architecture for the IM-Agents and preliminary experiments. In 2003, Susan *et al*. reported on detailed requirements and feature of IM-Agents based system that resulted due to medical collaboration. The selected approach and architecture are described in detail. Results of a prototype implementation at an emergency trauma centre are discussed. Mouratidis *et al*. (2002), describe the development effort of an electronic Single Assessment Process (eSAP) towards an integrated assessment of social and healthcare needs of older adults. The eSAP system is modelled using the TROPOS methodology and the design of the system is done using the Agent Technology. Moreno *et al*. describe the design and development of a Multi Agent System (MAS) which is composed of agents that provide medical services. This project lies within the framework of Agent Cities project whose aim is to build agent based information system for mobile users. Tablado *et al*. (2003) proposed a system using intelligent agents for remote monitoring of patients suffering from Parkinson disease. Except for Tablado *et al*. (2003), none of these systems have proposed the usage of intelligent agents in conjunction with the PDAs, as is proposed in the current research. The use of intelligent agents in healthcare is still in its infancy but the future holds tremendous promises of deploying intelligent agents in a large scale mobile users. Some of the major telecommunication companies such as Motorola, Fujitsu and BT are taking great initiatives in providing accessibility to agent based services via mobile devices such as mobile phones, PDAs or portable PCs (Moreno and Isern, 2002).

The system proposed in the current research is targeted to provide continuous monitoring of cardiac events among current patients suffering from cardiac diseases, those who do not yet have any known cardiac ailment but are at high risk based on past family history, *etc*. and those who have infrequent symptoms such as arrhythmias and ischemia representing approximately 85% of the patients suffering from cardiac ailments (Gouaux *et al*., 2003). In particular, the system is intended to be used by the elderly segment of the population who typically suffer from chronic cardiac diseases and require long-term hospitalisations and monitoring. The aim is to foster an environment where patients act as consumers of healthcare services, taking control of their individual health and playing a more active role in managing their ailment (cardiac ailment in the current case) and soliciting specialised professional healthcare only when needed. In the current context, the proposed system will not only ensure continuous monitoring of the cardiac patients for any anomalous events but will also provide them with an independent life outside the hospital or a nursing home. Professional care from the healthcare system will provide support to systems emphasising self-care and will be used as an infrastructure for specialised care. In addition to saving lives lost due to undetected symptoms or late diagnosis/treatment the proposed system will also economise the use of the scarce financial as well as human resources at the disposal of the healthcare sector.

The opportunities and advantages of a wireless ECG monitoring system for healthcare are numerous and so are the corresponding challenges associated with designing such a system. Some of the challenges of wireless ECG monitoring system and corresponding solutions proposed by the current research are outlined in Table 1.

Table 1 Challenges associated with cardiac-related deaths and proposed solution

Challenges	*Comments*	*Proposed solution*
Early detection of cardiac events in existing as well as potential patients	Result in a treatment without delay thereby reducing cardiac-related deaths.	Ubiquitous monitoring of people at risk of cardiac diseases will prevent the number of cardiac events that go unnoticed or fail to reach medical attention.
Reduction in healthcare costs while providing quality healthcare to patients	Increase in the size of aging population with cardiac ailments and increasing healthcare costs associated with prolonged hospitalisation.	Promoting continuous, remote monitoring of patients with cardiac ailments will result in saving healthcare costs associated with hospitalisation, which amounts to a large proportion of the healthcare expenditure.
Improved quality of life for cardiac patients and timely medical attention when needed	Increased hospitalisation not only increases costs but also reduces mobility and independence of patients.	Leverage mobile technologies to improve quality of healthcare and lifestyle of cardiac patients by the use of a system that could provide medical intervention as and when required in anomalous events.
Scalability of the system	The systems proposed for wireless ECG monitoring must be able to support large number of patients simultaneously.	Since the proposed solution sends ECG data from the patient to the healthcare centre only when an anomaly is detected, hence, it reduces unnecessary network traffic and is scalable.

Table 1 Challenges associated with cardiac-related deaths and proposed solution (continued)

Challenges	*Comments*	*Proposed solution*
Periodic surges	The system must be able to support patients in case there are a large number of patients sending alarm messages at the same time.	Prioritised transmission mechanism can be used to incorporate periodic surges. The priority for emergency messages or high-level alarms would take priority over low-level and medium-level alarms in case the volume of network traffic is high. Some WLANs allow prioritised routing such as IEEE 802.11b. The routing priority will need to be specified in the application layer, which will communicate to the transport layer.
Reliability	Reliability forms the cornerstone of remote monitoring especially when the consequences can be life threatening.	Reliability is achieved in the proposed solution by incorporating *ad hoc* networking along with infrastructure based networking for transmitting alarm messages.
Security	HIPAA has imposed security as a legal sanction on any healthcare transaction, thus making security of patient data a necessity.	Security of data transmitted over a wireless network is achieved by encoding the message and data in XML and encapsulating the encoded ECG data in SCP-ECG format. The use of XML makes the solution pervasive since any physician can analyse the alarm message without requiring any specialised software.
Privacy	HIPAA has imposed privacy as a legal sanction on any healthcare transaction, thus making privacy of patient's data a necessity.	The ID given to each patient is a random number, thus the ID by itself which is part of the alarm message is not sufficient to identify a patient. The location information of the patient is important to provide quick medical assistance to a patient. So far there are no specified guidelines regarding ownership of location information.
Power supply	Most of the portable monitoring devices are battery operated and since most of the weight of the device comes from the battery, there is a trade-off between carrying a heavy device with more power or a lighter device requiring frequent charging.	The power consumption of the ECG monitor and the PDA of the patient can be conserved by allowing the device to go in the sleep mode in between two consecutive ECG recording and analysis. Since in the normal condition ECG is recorded and analysed every 10 seconds, thus, the devices could be configured to go in the sleep mode every 9 seconds. The PDA will also beep to inform the patient when the battery needs to be recharged.

Configuration of the patient's PDA

Before the patient starts using the monitoring system, the ECG Checker Agent located in the patient's PDA is configured by a physician based on the current/past conditions with respect to cardiac diseases of the patient, thus providing individual patient-centred care. The ECG is almost like a fingerprint and analysing changes in recorded ECG with respect to a reference ECG will reduce inter-patient variability and greatly enhance the sensitivity of the diagnosis to any changes in the cardiac activities as reflected in the analysis (Gouaux *et al*., 2003). Hence, to increase the specificity of the system and reduce chances of incorrect diagnosis, four reference ECG readings are stored in the patient's PDA. These prior ECG readings specify the thresholds against which analysis is performed and alarm is triggered if required.

The physician specifies the thresholds and individual patient's risk factors, which the ECG Checker Agent will refer to before triggering a low-, medium- or high-level alarm. The time interval between two ECG readings under normal conditions (Record ECG every 10 seconds) as well as abnormal conditions, *i.e.*, after detection of an anomalous reading, (Record ECG every 1 second for the next 1 minute) is also configured. Four different measures of ECG; ECG1, ECG2, ECG3, ECG4 are stored and used as references. ECG2 and ECG3 are measured during normal functioning of the patient. ECG4 can be stored during intensive activity or a prior reading (if available) of the patient which was higher than the range of normal ECG. ECG1 is the lower end and can be stored from a prior low reading of ECG (if available). In case a patient-specific ECG reading is not available for one or more of the thresholds, a generic ECG reading can be used instead.

The ontology that categorises the different alerts is based on the following logical statements:

- Normal Condition – Recorded ECG is between ECG2 and ECG3.
- Abnormal Conditions (Alert Range)
  1. Low Level Alarm – Recorded ECG is equal to ECG2 or ECG3 (ECG Recording is at the boundary level).
  2. Medium Level Alarm – Recorded ECG is between ECG3 and ECG4 (Above normal).

     Recorded ECG is between ECG2 and ECG1 (Below normal).
  3. High Level Alarm – Recorded ECG is above ECG4 or below ECG1 (Emergency level).

The ontology is built in each PDA by a specialist that describes the alerts that must be checked for every patient. Once the ECG Checker Agent is configured, it subscribes to the ECG Receiver Agent and informs the ECG Receiver Agent of the ECG thresholds (ECG2 AND ECG3) that it is interested in and the time interval between two ECG readings under normal conditions. Once the ECG Receiver Agent receives the message, it sends an agree message back to the ECG Checker Agent acknowledging the acceptance of the subscription.

4 Description and protocol for wireless ECG monitoring system

Table 2 below gives a detailed description of the functionality and protocol of each component in the Wireless ECG Monitoring System.

Table 2 Components, functionality and protocol associated with each component in the proposed system

Component name	*Objective/functionality*	*Protocol*
ECG monitor	To measure the ECG of the patients The portable ECG is carried by the patient 24 hrs a day. The ECG device has two electrodes that are attached to the patient and provide a single channel ECG Signal (Nussbaum and Wu, 2002).	
PDA of the cardiac patient		
Bluetooth agent	The Bluetooth agent resides in the PDA and retrieves ECG readings from the wireless ECG monitor (Tablado *et al*., 2003).	
ECG Receiver agent	The ECG Receiver receives ECG data via Bluetooth, checks the ECG data for any anomalous conditions. If an anomalous condition is detected, then it sends the message to ECG Checker regarding the presence of the anomalous situation.	IF ECG[E]<=ECG2 OR IF ECG[E] >=ECG3 START INTENSIVE MONITORING (record ECG readings every 1 second for the next 1 minute) AND GENERATE MESG TO THE ECG CHECKER WITH EACH ECG[E] READ OVER THE NEXT 1 MINUTE ELSE CONTINUE NORMAL ECG RECORDINGS

ECG checker agent	The ECG Checker analyses the ECG data received from ECG Sensor and requests an intensive monitoring. The ECG data received for the 1 minute is analysed based on the alert conditions defined in the ontology and accordingly a low-, medium- or high-level alarm is triggered if required. The alarm triggered is sent to the Alarm Receiver at the Health Care Center along with a report including the patient's ID, Name, DOB, Blood Group, Current location, and the ECG readings over the past 1 minute and prescription drugs. The data is transmitted via Wireless Communication Network.	AnomalousCondExist =1
		Counter = 0
		WHILE (AnomalousCondExist AND Counter < 60)
		{IF ECG[E] = ECG2 OR ECG[E] = ECG3
		ALARMLEVEL = LOW
		//ECG reading on the lower or upper normal boundary conditions
		ELSE IF ECG[E] < ECG2 AND ECG[E] >
		ECG1
		ALARMLEVEL = MEDIUM
		ELSE IF ECG[E] > ECG3 AND ECG[E] < ECG4
		ALARMLEVEL = MEDIUM

Table 2 Components, functionality and protocol associated with each component in the proposed system (continued)

Component name	*Objective/functionality*	*Protocol*

		// ECG reading below or above normal
		ELSE IF ECG[E] < ECG1 OR ECG[E] > ECG4
		ALARMLEVEL = HIGH
		// ECG readings in the emergency level
		ELSE AnomalousCondExist = 0
		Counter ++}
		IF (AnomalousCondExist)
		SEND ALARM MESSAGE TO THE ALARM RECEIVER AT THE HC
		ELSE
		ECG CHECKER RETURNS TO NORMAL STATE, SENDS MESG. TO THE ECG SENSOR TO RETURN TO NORMAL INTERVAL FOR CHECKING ECG.
		// Not all ECG readings recorded were in the alert zone
		// ALARM MESSAGE
		ALRM MSG [PATIENT'S ID, DOB, PRESCRIPTION DRUGS, BLOOD GROUP, CURRENT LOCATION, ECG READINGS OVER THE PAST 1 MIN., LEVEL OF ALARM]
		// The patient's ID can be used to access the Electronic Health Record of the patient by an authorised personnel
		// The message and data will be encoded in XML. ECG readings will be encoded in SCP-ECG format (Medical Informatics, 2003) and bundled together in the message encoded in XML

Localisation agent	Localisation agent uses GPS (Global Positioning Satellite Systems) and/or other location tracking systems (WLANs, Radio Frequency Identification (RFID), *etc.*) to determine the present location of the patient.	The exact location of the patient can be obtained by acquiring signal from four GPS satellites. The localisation agent updates the location of the patient every 10 seconds. The present architecture of the system can be implemented using GPS, RFID, WLANs or any combination of the others. GPS is best suited for outdoor environments. RFID grid, which identifies objects uniquely using short-range communications is well suited for indoor environments (Varshney, 2005).

Table 2 Components, functionality and protocol associated with each component in the proposed system (continued)

Component name	*Objective/functionality*	*Protocol*
Patient Info. agent	Stores information about the patient such as: ID, name, address, date of Birth (DOB), medical contacts information, scheduling information, blood group, prescription drugs.	
Health Care Center – ECG data is transmitted from the PDA to the Health Care Center via a wireless network regardless of the location of the patient within the coverage of the network (Nussbaum and Wu, 2002).		
Alarm Receiver agent	Receives alarm sent by the PDA of the patients along with the report. Sends the report received to Emergency Mgmt. And Medical Info. Agents. Sends acknowledgement to the ECG Checker agent confirming that the alert has been received and is being managed.	RECEIVE ALRM MSG SEND THE ALRM MSG TO EMERGENCY MGMT. AND MEDICAL INFO. SEND ACKNOWLEDGEMENT BACK TO ECG CHECKER AT PATIENT'S PDA
Emergency Mgmt. agent	In case of *low level alarm*, the patient is contacted and is scheduled for a visit. A message is sent to the patient's PDA for scheduling a visit to see the doctor. This will cause a message to flash on the PDA and sound a low-level beep so that the patient would take notice and contact the doctor. In case of a *medium level alarm*, a message is sent to the PDA of the doctor on call. The message consists of the level of alarm and the patient's report received from the Alarm Receiver Agent. The doctor analyses the ECG report, contacts the patient with the result of the analysis and schedules an appointment ASAP. If the doctor sees the need then the emergency unit is dispatched.	IF ALARMLEVEL = LOW MESSAGE SENT TO INFORMATION AGENT ON PATIENT'S PDA TO SCHEDULE A VISIT WITH THE DOCTOR ELSE IF ALARMLEVEL = MEDIUM SEND ALARM MESSAGE TO THE PDA OF DOCTOR // Doctor then analyses the alarm message and takes requisite actions. ELSE IF ALARMLEVEL = HIGH SEND ALARM MESSAGE TO THE EMERGENCY UNIT REQUESTING THE UNIT TO BE DISPATCHED TO THE PATIENT'S LOCATION IMMEDIATELY SEND ALARM MESSAGE TO THE PDA OF DOCTOR

Table 2 Components, functionality and protocol associated with each component in the proposed system (continued)

Component name	*Objective/functionality*	*Protocol*
	In case of a *high level alarm*, the emergency unit is contacted with the patient's location, ID and the ECG reading. A message is then sent to the PDA of the doctor on call. The message consists of the level of alarm and the patient's report received from the Alarm Receiver agent. The specialist analyses the ECG report and keeps the emergency unit abreast with the result via wireless communication.	
Medical Info. Agent	Update the patient's Electronic Medical Record (EMR) with the ECG report received from Alarm Receiver. The update includes the ECG report, the level of alarm triggered and the date of the event.	LOCATE PATIENT'S EMR IN THE CENTRAL DATABASE USING PATIENT'S ID AS KEY UPDATE PATIENT'S EMR WITH THE INFORMATION PROVIDED IN THE ALARM MESSAGE, DATE OF THE ALARM EVENT.
PDA of the doctor		
Alert Receiver agent	Receives alarms from Emergency Mgmt. agent and sends a confirmation to the Emergency Mgmt. Once the doctor has received the message and acknowledged the alarm by responding to it. Sounds a medium or high level beeps along with flashing the alarm message on the doctor's PDA so that the doctor takes notice of the alarm sent.	
Patient record agent	Queries the patient database on doctor's request and updates the database with information provided by the doctor.	

Figure 2 below, represents the logical flow of information between components/ intelligent agents of the wireless ECG monitoring system and depicts the computation and analysis made by the intelligent agents housed in the patient's PDA, the healthcare centre, and the doctor's PDA, thereby making monitoring of ECG of cardiac patients pervasive and less labour intensive. The anytime, anywhere component in the current research provides a pervasive solution since it is not limited to any particular wireless communication network and can be easily implemented utilising the existing wireless communication infrastructure. Besides, the continuous monitoring and reliability of message delivery can be enhanced by incorporating *ad hoc* network formed between patient's devices for sending alarm messages to the healthcare centre.

The fundamental components of the proposed system are the wireless ECG monitor, the PDA of the patient which carries intelligent analysis, the healthcare centre and the PDA carried by the doctor. The basic steps involved by the proposed system in wireless ECG monitoring include:

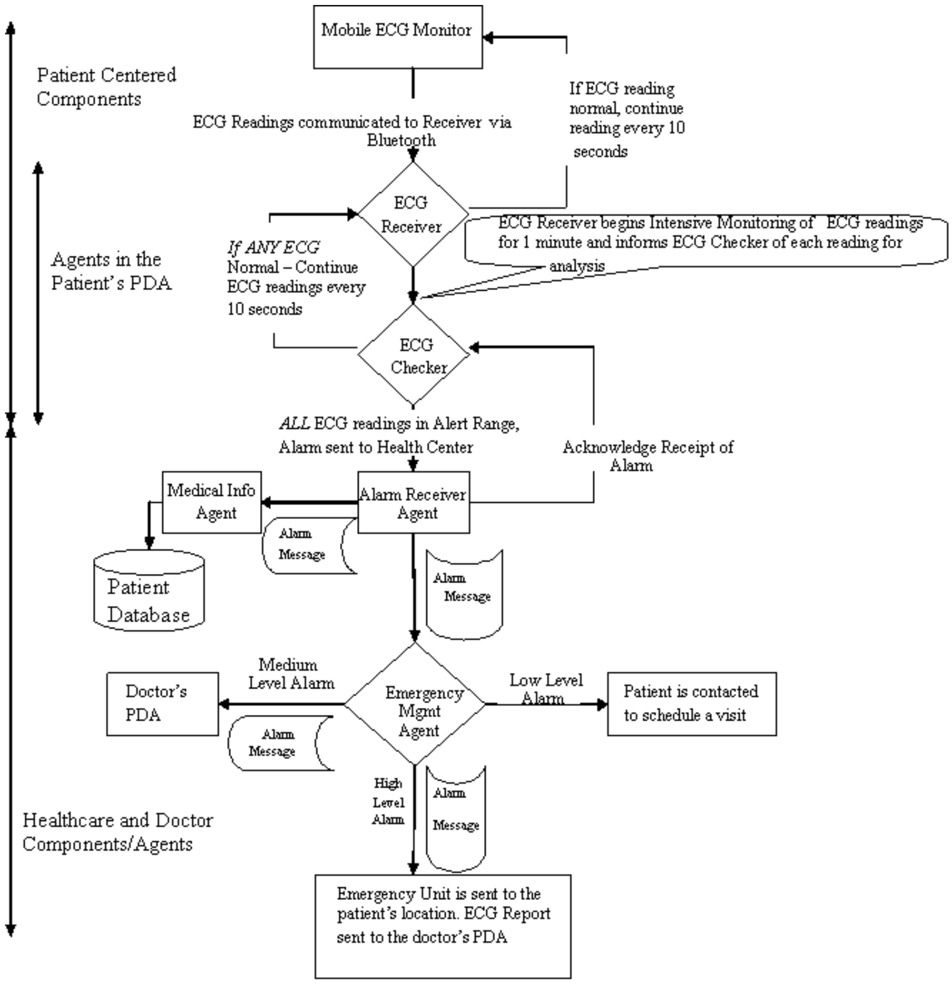
1 recording of ECG

2 receiving of ECG data via Bluetooth on the patient's PDA

3 analysis of ECG by the intelligent agents in the patient's PDA to detect the presence of anomalies

4 sending alarms to the healthcare centre if anomalies detected otherwise continue normal monitoring.

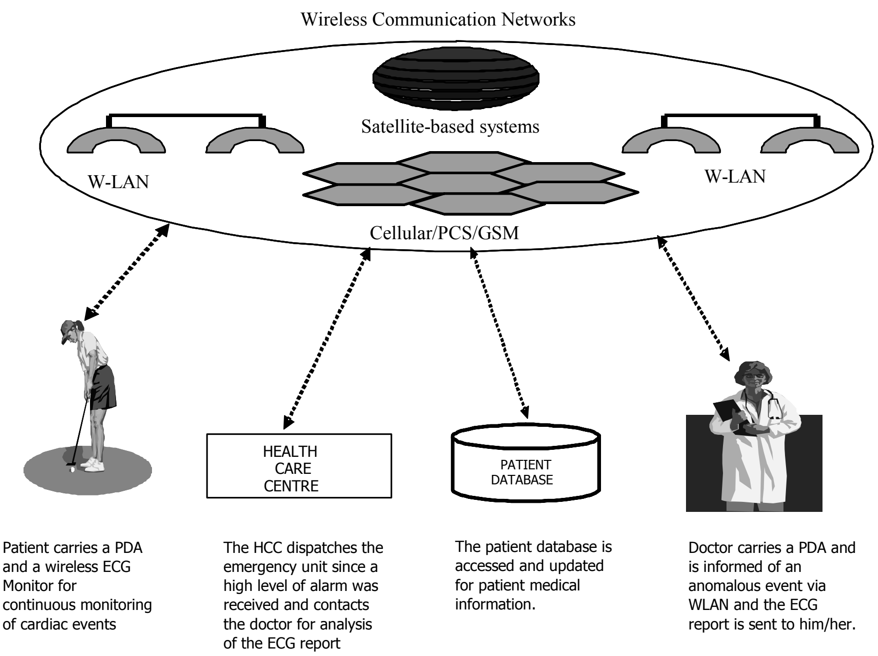
Figure 2 Information flow between components/intelligent agents of wireless ECG monitoring system



5 Usage scenario of wireless ECG monitoring system

Let us consider the case of a cardiac patient who is 50 years old and needs continuous monitoring of the heart to detect any changes in the cardiac events. The doctor has prescribed him to use the wireless ECG monitoring system. His PDA has been configured with the threshold ECG readings and the alerts have been categorised. On one beautiful day, he went out to play golf and on the golf course he had a cardiac arrest. Figure 3 below represents the usage scenario. At that moment, in the continuous monitoring cycle of the ECG Receiver agent an ECG reading was recorded that detected an anomalous event. The ECG Checker agent was informed of the situation, which requested the ECG Receiver Agent to continue monitoring the ECG recordings every second over the next one minute and to be informed of each recording. If any of the ECG readings recorded over the one minute time interval falls in the normal recording range (as defined by the ontology) then the ECG Checker agent returns to the normal state and informs the ECG Receiver Agent to continue the normal recording and cancel the intensive recordings. But since all the ECG recordings fall in the abnormal range so an alarm is triggered and a message sent to the Alarm Receiver agent of the Health Care Center (HCC). Suppose the alarm was a high level alarm. The Alarm Receiver agent contacts the Emergency Mgmt. agent and the Medical Info. agent with the message received from the ECG Checker agent at the PDA of the patient. Since the alarm is a high level alarm, an ambulance is immediately dispatched to the location of the patient while the doctor on call analyses the ECG report and guides the healthcare professionals on the way to the patient and tells them exactly how to stabilise the patient. The ambulance reaches the victim in time and since the ECG report has already been analysed, no time is lost and the victim is resuscitated. The patient's record is updated.

Figure 3 Usage scenario



In the absence of the wireless ECG monitoring system, the cardiac arrest could have been fatal since there was no way to get help on a golf course where there was no one in close proximity to the patient. Even if there was someone around, it would have taken sometime for the person to realise what was happening and since the medical team had no way of knowing the current state of the victim, a few extra minutes would have been lost in diagnosing the extent of the cardiac event. In a cardiac arrest, where the difference of a minute means the difference between life and death, the importance of ubiquitous monitoring of cardiac events in preventing fatalities and promoting well-being of cardiac patients is phenomenal.

Before the patient will start using the monitoring system, the ECG Checker agent located in the patient's PDA will be configured by a physician based on the current/past conditions of the patient, thus providing individual patient-centred care.

Another typical usage of the system could be envisioned in the case where a person using the system does not have any prior cardiac ailments yet but is on high-risk because of past medical condition and/or family history. The doctor has asked the person to use the wireless ECG monitor in order to detect early signs of cardiac disease if present and start the treatment as soon as any signs are detected. If the system detects the presence of an anomaly, then the appropriate level of alarm is sent to the healthcare centre and the patient is provided treatment and help thereafter. This would not only help in early detection and treatment of cardiac ailments which would have otherwise gone unnoticed resulting in longer treatment and higher healthcare expenses but will also reduce fatalities associated with cardiac disease, caused outside the hospital.

6 Current issues and future research

It is our hope that some of the current issues will open the door for future research. The current research proposes the use of mobile technologies to address the problem of rising healthcare costs in context to long-term hospitalisations, monitoring and treatment of cardiac patients in addition to early detection and reduction in cardiac-death victims. The use of wireless solutions has multiple advantages and it brings unique opportunities for patients, doctors and healthcare industry and can be leveraged to changing healthcare environment, but at the same time it brings challenges of its own (Kara, 2001).

The current research has proposed an architectural framework for pervasive monitoring of cardiac patients. The next step in this direction of research would entail creating a prototype and evaluating it to assess the feasibility of intelligent agents in continuous monitoring of cardiac patients anytime, anywhere. The feasibility analysis will be useful in revealing the actual usability and loopholes in the proposed system.

In the light of HIPAA, security and reliability of transactions made over a wireless network are important concerns. Since critical patient information is transacted in the wireless solution, hence there is a need to provide secure healthcare transaction environment while providing high quality healthcare (Wickramasinghe *et al*., 2005). The use of *ad hoc* wireless network to augment the current wireless networks is a viable option to increase the reliability of patient monitoring (Varshney, 2004).

The proposed solution would not only result in cost saving as healthcare resources can be utilised more efficiently but would also reduce the burden on the labour force in the healthcare sector. Goldberg and Wickramasinghe (2003) have already shown that usage of wireless technologies to support healthcare functionality has marked cost benefits. However, a detailed cost-benefit analysis including several cost factors such as cost of medical equipment, PDA, location-monitoring by multiple technologies, and cost of responding medical personnel versus the cost of long-term hospitalisations and treatment of cardiac diseases which were not detected in the early stages, needs to be done to empirically establish the benefits.

The issue of usability of the system along with the level of trust of doctors and patients in the system should be studied in order to make the system pervasive. The aging population suffering from heart diseases and requiring prolonged hospitalisation due to continuous monitoring of heart are willing to begin using wireless and mobile technologies as long as these technologies would truly provide independence along with ubiquitous monitoring (Varshney, 2003).

Furthermore, the success of m-health requires a giant paradigm shift in the way healthcare is delivered and practiced (Wickramasinghe *et al*., 2005). The adoption and success of wireless solution proposed depends on the willingness of the major stakeholders such as doctors, patients and healthcare providers to adopt the technology.

Another direction for future research in the field of cardiac diseases is the possibility of implanting electrodes in the body of patients at risk of cardiac diseases or current patients who require continuous monitoring. This will eliminate errors in ECG readings caused by misplaced electrodes or electrodes falling out of place. Additionally, it would be a novelty if future research could get the architecture proposed in the current research to interface with the Implanted Cardioverter-Defibrillators (ICDs) so that when an electric jolt is administered, a wireless signal is sent directly to a cardiologist.

7 Conclusions

Cardiovascular disease is one of the major causes of untimely deaths in US ECG readings are by far the only viable diagnostic tool that could promote early detection of cardiac events. Wireless and mobile technologies are key components that would help enable patients suffering from chronic heart diseases to live in their own homes and lead their normal life, while, at the same time being monitored for any cardiac events. This will not only serve to reduce the burden on the dwindling resources of the healthcare centre but would also improve the quality of healthcare by adding the *anywhere*, *anytime* paradigm to the healthcare sector. In this paper, we presented an architectural framework of a system that utilises mobile technologies to enable continuous, wireless, ECG monitoring of patients anytime anywhere. The intelligent agents residing in the system detect any anomalous ECG readings and trigger an alarm that is sent to the healthcare centre in case of an emergency. Hence, the system would not only aid in early detection and treatment of cardiac events in addition to continuous monitoring of cardiac patients and an independent lifestyle but will also save healthcare costs associated with prolonged hospitalisation of cardiac patients.

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Notes

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