Wireless Sensor Networks for Medical Care

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Abstract

Recent technological advances in sensors, low-power integrated circuits, and wireless communications have enabled the design of low-cost, miniature, lightweight, and intelligent physiological sensor nodes. These nodes, capable of sensing, processing, and communicating one or more vital signs, can be seamlessly integrated into wireless sensor networks (WSNs) for health monitoring. These networks promise to revolutionize health care by allowing inexpensive, non-invasive, continuous, ambulatory health monitoring with almost real-time updates of medical records. They should reshape operating practices in clinical medicine, especially in monitoring a chronic disease's progression, and assessing postoperative care and body reaction to complex therapeutic drug regimes.

The aim of this study is to develop a platform for the research of wireless biomedical sensor networks (WBSN). A sensor node platform featuring an ultra low-power microcontroller, an IEEE 802.15.4 compatible transceiver is presented. The proposed solution promises a cost-effective, flexible platform that allows easy customization, energy-efficient computation and communication. We have also developed some sensors to monitor the body motions and the physiological signals including electrocardiogram (EKG), plethysmogram (PPG) and galvanic skin response (GSR). In addition to the hardware platform, the paper also presents software infrastructure for wireless sensor network. The software in the sensor node is developed based on TinyOS, an operating system designed for wireless embedded sensor networks. TinyOS features a component-based architecture which enables rapid innovation and implementation while minimizing code size as required by the severe memory constraints inherent in sensor networks. Finally, we describe two case studies: wearable wireless body area network for long-term health monitoring and a wireless sensor network for use by emergency responders during chaotic pre-hospital settings.

摘要

最近,在傳感器、低功耗電路以及無線通信上的技術進步已經使設計低價、體積小且重量輕的智能生理傳感器節點成為可能。這些具備傳感、處理和傳輸一個或多個生理信號能力的節點可以被無縫地集成在監控身體健康狀況的無線傳感器網絡里。這些傳感器網絡可以獲得醫療信號的實時更新來實現低價的、輕便的、連續的醫療監控，這也將勢必改觀現有的醫療保健系統。這些也將改變臨床醫學的操作實踐，特別是監控慢性病的進展、手術后的變化以及身體對復雜治療體制的反應。

本論文的研究目的是開發一個用作無線醫療傳感器網絡研究的平臺。本文將介紹一個具有低功耗微控制器和符合 IEEE 802.15.4 協議的收發器的傳感器節點平臺。這個平臺是低價而且通用的，可以輕易實現擴展和低能耗的計算和無線傳輸。我們還開發了監視身體動作和心電圖、血氧濃度以及流電皮膚反應的系列傳感器。除了硬件結構，本文還介紹無線傳感器網絡的軟件。傳感器節點的軟件是基于 TinyOS 這個專門為無線傳感器網絡設計的操作系統開發的。TinyOS 有一個基于組件的結構，能實現方便的創新開發，同時保證代碼最少化，以適應傳感器網絡設備的內存限制。最后，我們實現了兩個實際案例：用于長期醫療監控的可穿戴無線軀域傳感器網絡

和用于急救的無線傳感器網絡。

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Chapter 1 Introduction

A wireless sensor network (WSN) is a network that consists of a large number of small devices, which are in fact tiny computers [1]. These so-called nodes (or motes) are composed of a power supply, a microprocessor, different kinds of memory and a radio transceiver for communication. Wireless sensor networks are generally used to observe or sense the environment in a non-intrusive way.

The domain of wireless sensor networks is still very young [2][3]. During the last few years, new developments in the area of communication, computing and sensing have enabled and stimulated the miniaturization and optimization of computer hardware. These evolutions have led to the emergence of wireless sensor networks. Despite the increasing capabilities of hardware in general, sensor nodes are still very restricted devices. They have a limited amount of processing power, memory capacity and most importantly energy. Therefore, most of the existing operating systems, programs and even algorithms are not suitable for WSNs. Their processing and memory requirements are too high given the constraints of sensor nodes, and power consumption would be exhaustive. This makes wireless sensor networks a challenging research topic. The main research target is the overall reduction of power consumption. Therefore, research is done on the implementation of small and capable operating systems and on the construction of efficient algorithms, in terms of energy, processing power and memory footprint.

1.1 Design Challenges

Several design challenges present themselves to designers of wireless sensor network applications [4]. The limited resources available to individual sensor nodes imply designers must develop highly distributed, fault-tolerant, and energy-efficient applications in a small memory-footprint. Consider the latest-generation MICAz [5] sensor node shown in Figure 1-1.

Figure 1-1: MICAz sensor mote hardware.

MICAz motes are equipped with an Atmel128L processor capable of a maximum throughput of 8 millions of instructions per second (MIPS) when operating at 8 MHz. It also features an IEEE 802.15.4 compliant RF transceiver, operating in the 2.4-2.4835GHz globally compatible industrial scientific medical (ISM) band, a direct spread-spectrum radio resistant to RF interference, and a 250-kbps data transfer rate. The MICAz runs on TinyOS and is compatible with existing sensor boards that are easily mounted onto the mote. A partial list of specifications given by the manufacturers of the MICAz mote is presented in Table 1-1.

Processor	Atmel AtMega128L@8Mhz
Program Flash Memory	128 KBs
EEPROM	4KBs
Serial Communications	UART
Analog to Digital Converter	10bit ADC
Other Interface	Digital I/O, I2C, SPI
Processor Current Draw	8mA in active mode <1μA in sleep mode
Frequency band	2400MHz to 2483.5MHz
Transmit data rate	250kbps
RF power	-24dBm to 0dBm
Receive Sensitivity	-90dBm(min), -94dBm(typ)
Outdoor Range	75m to 100m
Indoor Range	20m to 30m
Radio Current Draw	19.7mA in receive mode 11mA(TX -10dBm) 14mA(TX -5dBm) 17.4mA(TX 0dBm) 20μA in idle mode 1μA in sleep mode
Battery	2AA batteries
Weight	0.7oz
Size	2.25*1.25*0.25inch

Table 1-1: MICAz mote specifications.

For wireless sensor network applications to have reasonable longevity, an aggressive energy-management policy is mandatory. This is currently the greatest design challenge in any wireless sensor network application. Considering that in the MICAz mote the energy cost associated with transmitting a byte over the transceiver is substantially greater than performing local computation, developers must leverage local processing capabilities to minimize battery-draining radio communication. Several key differences between more traditional ad hoc networks and wireless sensor networks exist:

- Individual nodes in a wireless sensor network have limited computational power and storage capacity. They operate on nonrenewable power sources and employ a short-range transceiver to send and receive messages.
- The number of nodes in a wireless sensor network can be several orders of magnitude higher than in an ad hoc network. Thus, algorithm scalability is an important design criterion for sensor network applications.
- Sensor nodes are generally densely deployed in the area of interest. This dense deployment can be leveraged by the application, since nodes in close proximity can collaborate locally prior to relaying information back to the base station.

Sensor networks are prone to frequent topology changes. This is due to several reasons, such as hardware failure, depleted batteries, intermittent radio interference, environmental factors, or the addition of sensor nodes. As a result, applications require a degree of inherent fault tolerance and the ability to reconfigure themselves as the network topology evolves over time. Wireless sensor networks do not employ a point-to-point communication paradigm because they are usually not aware of the entire size of the network and nodes are not uniquely identifiable. Consequently, it is not possible to individually address a specific node. Paradigms, such as directed diffusion, employ a data-centric view of generated sensor data. They identify information produced by the sensor network as attribute, value pairs. Nodes request data by disseminating interests for this named data throughout the network. Data that matches the criterion are relayed back toward the querying node.

Even with the limitations individual sensor nodes possess and the design challenges application developers face, several advantages exist for instrument an area with a wireless sensor network:

- Due to the dense deployment of a greater number of nodes, a higher level of fault tolerance is achievable in wireless sensor networks.
- Coverage of a large area is possible through the union of coverage of several small sensors.
- Coverage of a particular area and terrain can be shaped as needed to overcome any potential barriers or holes in the area under observation.
- It is possible to incrementally extend coverage of the observed area and density by deploying additional sensor nodes within the region of interest.

- An improvement in sensing quality is achieved by combining multiple, independent sensor readings. Local collaboration between nearby sensor nodes achieves a higher level of confidence in observed phenomena.

1.2 Wireless Sensor Network Applications

Despite current restrictions, several applications have been envisioned for wireless sensor networks. These range in scope from military applications to environment monitoring to biomedical applications [6][7][8]. This section discusses proposed and actual applications that have been implemented by various research groups.

The military world uses wireless sensor networks in hostile environments to spy on the enemy in a safe, non-intrusive way. In the medical world, they are used to improve the process of treating and following-up patients. Wireless sensor networks are found in civil applications too, for monitoring and protecting public property. In control and automation applications, they aim at monitoring and improving industrial processes and in safety and security applications; they try to protect people and private property from malicious attacks. WSNs are also used for environmental monitoring, which is the long-term observation of natural phenomena, fauna and flora, in a non-intrusive way. The observation data is studied and measures can be taken to adapt the environment if necessary. Finally, they are found in home applications, to ease people's life by making the home environment smarter in any possible way. When talking about smart home environments, one could in the first place think of obvious functional applications, like the lights being turned on automatically when it gets dark or the air conditioning being turned on when it is getting too warm. At the domain of Industrial Design Engineering (IDE), researchers want to exploit the possibilities of WSNs even further. Their goal is to create complete atmospheres, in which the settings for among others light and music are defined. These atmospheres can subsequently be linked to activities. One could for example think of a warm atmosphere, with quiet music and dim lights, for intimate or familial activities.

1.2.1 Military Applications

Wireless sensor networks can form a critical part of military command, control, communications, computing, intelligence, surveillance, reconnaissance, and targeting (C4ISRT) systems. Examples of military applications include monitoring of friendly and enemy forces; equipment and ammunition monitoring; targeting; and nuclear, biological, and chemical attack detection.

By equipping equipment and personnel with sensors, their condition can be monitored more closely. Vehicle, weapon, and troop-status information can be gathered and relayed back to a command center to determine the best course of action. Information from military units in separate regions can also be aggregated to give a global snapshot of all military assets.

By deploying wireless sensor networks in critical areas, enemy troop and vehicle movements can be tracked in detail. Sensor nodes can be programmed to send notifications whenever movement through a particular region is detected. Unlike other surveillance techniques, wireless sensor networks can be programmed to be completely passive until a particular phenomenon is detected. Detailed and timely intelligence about enemy movements can then be relayed, in a proactive manner, to a remote base station.

In fact, some routing protocols have been specifically designed with military applications in mind. Consider the case where a troop of soldiers needs to move through a battlefield. If the area is populated by a wireless sensor network, the soldiers can request the location of enemy tanks, vehicles, and personnel detected by the sensor network (Figure 1-2). The sensor nodes that detect the presence of a tank can collaborate to determine its position and direction, and disseminate this information throughout the network. The soldiers can use this information to strategically position themselves to minimize any possible casualties.

In chemical and biological warfare, sensor networks deployed in friendly regions can be used as early-warning systems to raise an alert whenever the presence of toxic substances is detected. Deployment in an area attacked by chemical or biological weapons can provide detailed analysis, such as concentration levels of the agents involved, without the risk of human exposure.

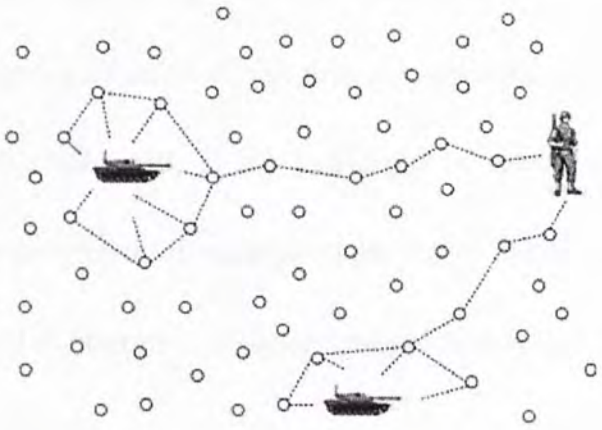


Figure 1-2: Enemy target localization and monitoring.

1.2.2 Environmental Applications

By embedding a wireless sensor network within a natural environment, collection of long-term data on a previously unattainable scale and resolution becomes possible. Applications are able to obtain localized, detailed measurements that are otherwise more difficult to collect. As a result, several environmental applications have been proposed for wireless sensor networks. Some of these include habitat monitoring, animal tracking, forest-fire detection, precision farming, and disaster relief applications.

Habitat monitoring permits researchers to obtain detailed measurements of a particular environment in an unobtrusive manner. For example, applications such as the wireless sensor network deployed on Great Duck Island [9] allow researchers to monitor the nesting burrows of Leach's Storm Petrels without disturbing these seabirds during the breeding season. Deployment of the sensor network occurs prior to the arrival of these offshore birds. Monitoring of the birds can then proceed without direct human contact. Similarly, the PODS project [10] at the University of Hawaii uses wireless sensor networks to observe the growth of endangered species of plants. Data collected by the sensor network is used to determine the environmental factors that support the growth of these endangered plants.

Consider a scenario where a fire starts in a forest. A wireless sensor network deployed in the forest could immediately notify authorities before it begins to spread uncontrollably (see Figure 1-3). Accurate location information about the fire can be quickly deduced. Consequently, this timely detection gives firefighters an unprecedented advantage, since they can arrive at the scene before the fire spreads uncontrollably.

Figure 1-3: Forest-fire monitoring application.

1.2.3 Health Applications

Potential health applications abound for wireless sensor networks [11][12]. Conceivably, hospital patients could be equipped with wireless sensor nodes that monitor the patients' vital signs and track their location. Patients could move about more freely while still being under constant supervision. In case of an accident (say the patient trips and falls), the sensor could alert hospital workers as to the patient's location and condition. A doctor in close proximity, also equipped with a wireless sensor, could be automatically dispatched to respond to the emergency.

Glucose-level monitoring is a potential application suitable for wireless sensor networks. Individuals with diabetes require constant monitoring of blood sugar levels to lead healthy, productive lives. Embedding a glucose meter within a patient with diabetes could allow the patient to monitor trends in blood-sugar levels and also alert the patient whenever a sharp change in blood-sugar levels is detected. Information could be relayed wirelessly from the monitor to a wristwatch display. It would then be possible to take corrective measures to normalize blood sugar levels in a timely manner before they get to critical levels. This is of particular importance when the individual is asleep and may not be aware that their blood- sugar levels are abnormal.

1.3 Wireless Biomedical Sensor Networks (WBSN)

An emerging application for wireless sensor networks involves their use in medical care. They are called wireless biomedical sensor networks (WBSN) [13][14]. These networks promise to revolutionize health care by allowing inexpensive, non-invasive, continuous, ambulatory health monitoring with almost real-time updates of medical records. In a hospital or clinic, outfitting every patient with tiny, wearable wireless vital sign sensors would allow doctors, nurses and other caregivers to monitor continuously the status of their patients. In an emergency or disaster scenario, the same technology would enable medics to more care for large numbers of casualties effectively. First responders could receive immediate notifications on any changes in patient status, such as respiratory failure or cardiac arrest. Wireless sensors could augment or replace existing wired telemetry systems for many specific clinical applications, such as physical rehabilitation or long-term ambulatory monitoring. Despite the increased interest in this area, a significant gap remains between existing sensor network designs and the requirements of medical monitoring. Most sensor networks are intended for deployments of stationary nodes that transmit data at relatively low data rates. By contrast, medical monitoring requires relatively high data rates, reliable communication, and multiple receivers (e.g. PDAs carried by doctors and nurses). Moreover, unlike any sensor network applications, medical monitoring cannot make use of traditional in-network aggregation since it is not generally meaningful to combine data from multiple patients. Companies such as Nonin [15] have developed wireless vital sign sensors based on Bluetooth technology, while Harvard's ColdBlue project [16] has developed an RF-based location-tracking system (called MoteTrack [17]) for use in hospitals. Other research projects include the European Commission's wide-ranging MobiHealth Project, which aims to provide continuous monitoring of patients outside the hospital environment by developing the concept of a 3G-enabled "Body-Area Network" The potential applications will save lives, create valuable data for medical research, and cut the cost of medical services.

1.4 Text Organization

In this thesis, a detailed discussion of the different aspects of implementing a wireless sensor network for biomedical information monitoring is presented.

Chapter 2 discusses how to construct a sensor node platform in both hardware and software respective.

Chapter 3 discusses the sensors that are commonly used in physiological signal monitoring. We also discuss location tracking and motion tracking techniques.

Chapter 4 discusses the application scenarios of wireless biomedical sensor networks, including wearable wireless body area network and applications in ambulatory conditions.

Chapter 5 summarizes the thesis and states the directions for future research.

Chapter 2 Design a Wearable Platform for Wireless Biomedical Sensor Networks

Design of low-cost, miniature, lightweight, ultra low-power, flexible sensor platform capable of customization and seamless integration into a wireless biomedical sensor network(WBSN) for health monitoring applications presents one of the most challenging tasks. In this section, we propose a WBSN node platform (called MediMesh mote) featuring an ultra low-power microcontroller, an IEEE 802.15.4 compatible transceiver, and a flexible expansion connector. The proposed solution promises a cost-effective, flexible platform that allows easy customization, energy-efficient computation and communication. The development of a common platform for multiple physical sensors will increase reuse and alleviate costs of transition to a new generation of sensors.

The last decade has witnessed a significant surge of interest in sensing and monitoring in healthcare. Many patients can benefit from continuous monitoring as a part of a diagnostic procedure, optimal maintenance of a chronic condition or during supervised recovery from an acute event or surgical procedure. As more and more biomedical sensors emerging, there are heavy demands of wireless connection.

Wireless Sensor Network is becoming a promising technology for various applications. One of its potential deployments is in the form of wireless biomedical sensor network (WBSN) for measuring physiological signals. The architecture of a WBSN is illustrated in Figure 2-1. The miniature wireless intelligent module which can be integrated with some kind of biosensor is referred as WBSN node. Physiological signals (EEG, ECG, SpO2, temperature, blood pressure, glucose level, etc.) measured by wearable or implantable biosensors are gathered by body area network head (BAN-Head) wirelessly. The BAN-Head can be WBSN node itself or any portable device, such as a PDA of a cell phone. The BAN-Head with sufficient computation ability can do data analysis locally, detect abnormalities of patients' physiological condition and provide alerts immediately. The BAN-Head also behaves as a router between nodes and server via short-range (ZigBee/Bluetooth/WIFI) of long-range (GSM/GPRS/3G) network. The server stores the data into patient database, do long term trend analysis and prediction. The healthcare professionals and patients can access the long term physiological data via internet.

WBSN, unlike wired monitoring systems, provide long term and continuous monitoring of patients under their natural physiological states even when they move. The system allows unobtrusive ubiquitous monitoring and can generate early warnings if received signals deviate from predefined personalized ranges.

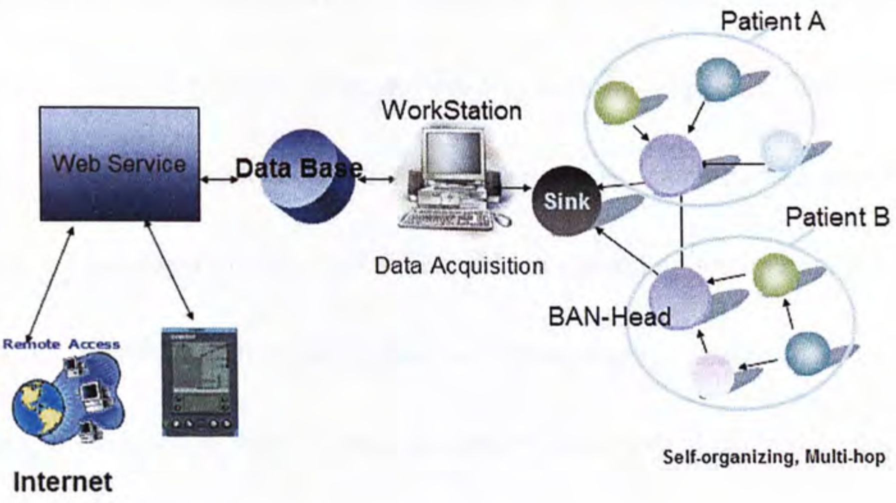


Figure 2-1: Architecture of a wireless biomedical sensor network.

Up to now, most of the WSN hardware platforms are designed for network research, or environment monitoring, such as Berkeley's Mica2 and Telos, ETH's BTnodes, and Intel's iMote. To facilitate the research of WBSN, a WBSN specified node platform needs to be developed. The realization of miniature and lightweight WBSN nodes poses one of the most challenging tasks for designers. As sensor nodes are battery powered and have stringent requirements for size and weight, they must be extremely energy-efficient in order to avoid inconvenience due to frequent battery charges.

2.1 Objective

The objective of this work is to design an embedded system, which includes software and hardware components, which will be a prototype device for wireless sensor networks.

Embedded system is a combination of computer hardware and software, and perhaps additional mechanical or other parts, designed to perform a specific function. They are present in equipments such as electric coffee machines, cameras and mobile phones. Compared to personal computers that are capable of executing innumerous tasks, they are designed for specific functionalities, such as controlling the sparks in a car engine or controlling a microwave oven. Using microcontrollers and microprocessors for these tasks allows automation of manual tasks. Many microcontrollers have been developed for specific applications in a way to aggregate a set of small functionalities. For example, advanced mathematical functions do not need to be present in a coffee machine microcontroller. The small cost of these devices allows their uses at a great number of applications. Embedded systems compromise cost with functionalities. In this way, a minimal hardware and software should be utilized to attend system requirements and minimize cost. Sensor nodes can be seen as a special case of embedded systems and benefit from the large body of knowledge already exist.

This sensor node prototype is called MediMesh mote (Figure 2-2). In this section, the design considerations and component choices for a prototype device for WBSN will be discussed. We present the state-of-the-art for sensor node architectures, investigating and analyzing some of the architectural challenges posed by these devices.

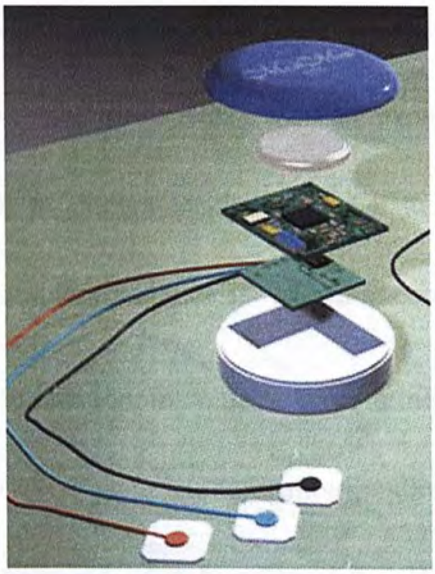


Figure 2-2 MediMesh mote: a sensor node prototype.

2.2 Requirements for Wireless Medical Sensors

Wireless medical sensors should satisfy the main requirements such as energy efficiency, cost, wearability, reliability, security, and interoperability.

Energy efficiency. The hardware must be energy efficient due to the limited battery capacity. The hardware should be able to estimate how much energy is left, so that algorithms can adapt to the available power.

Cost. Wireless sensor networks will be deployed in large number of nodes; hence the price per node must be at a minimum.

Wearability. To achieve non-invasive and unobtrusive continuous health monitoring, wireless medical sensors should be lightweight and small. The size and weight of sensors is predominantly determined by the size and weight of batteries. But then, a battery's capacity is directly proportional to its size. We can expect that further technology advances in miniaturization of integrated circuits and batteries will help designers to improve medical sensor wearability and the user's level of comfort.

Reliability. Reliable communication in WBSN is of utmost importance for medical applications that rely on WBSN. The communication requirements of different medical sensors vary with required sampling rates, from less than 1 Hz to 1000 Hz. One approach to improve reliability is to move beyond telemetry by performing on-sensor signal processing. For example, instead of transferring raw data from an ECG sensor, we can perform feature extraction on the sensor, and transfer only information about an event (e.g., QRS features and the corresponding timestamp of R-peak). In addition to reducing heavy demands for the communication channel, the reduced communication requirements save on total energy consumption, and consequently increase battery life. A careful trade-off between communication and computation is crucial for optimal system design.

Security. Another important issue is overall system security. At the lowest level, wireless medical sensors must meet privacy requirements mandated by the law for all medical devices and must guarantee data integrity. Though key establishment, authentication, and data integrity are challenging tasks in resource constrained medical sensors, a relatively small number of nodes in a typical WBSN and short communication ranges make these tasks achievable.

Interoperability. The hardware design must be expandable with a number of sensors.

2.3 Hardware design

In this section we describe a WBSN node platform capable of supporting a wide range of medical monitoring applications. The design of the initial sensor platform relies on commercially off-the-shelf (COTS) technology. By adopting IEEE 802.15.4 standards, the node provides compatibility and interoperability with other 802.15.4 networks.

2.3.1 Materials and Methods

T he proposed architecture of WBSN node platform is shown in Figure 2-3.

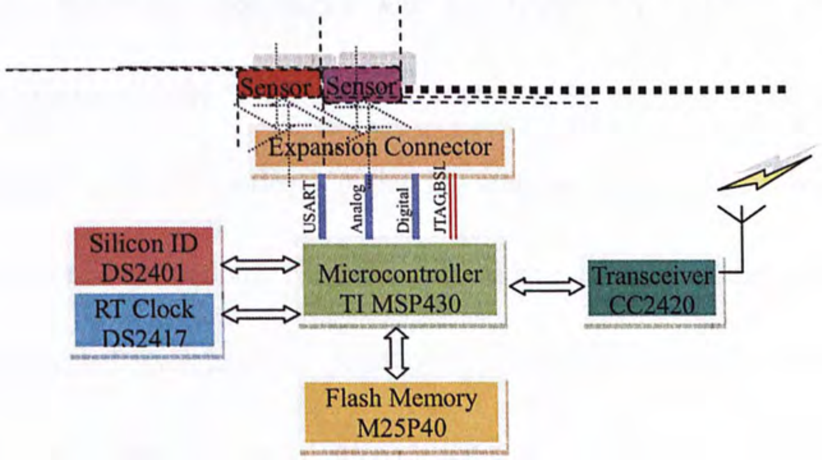


Figure 2-3: The architecture of WBSN node platform.

The core of the WBSN node is the ultra low power Texas Instruments MSP430 F1611 microcontroller featuring 10kB of RAM, 48kB of flash, 128B of information storage, and 8-channels of 12-bit A/D converters. This 16-bit RISC processor features extremely low current consumption (less than 1 mA in active mode and about ~1 μA in standby mode) that permits the node to run for a long time. Internal microcontroller analog channels monitor battery voltage and temperature. Therefore, the battery status and temperature can be accessed by the monitoring program.

The node platform features the ChipCon CC2420 radio for wireless communications. The CC2420 is an IEEE 802.15.4 compliant radio providing the PHY and some MAC functions. With sensitivity exceeding the IEEE 802.15.4 specification and low power operation, the CC2420 provides reliable wireless communication. The CC2420 is highly configurable for many applications with the default radio settings providing IEEE 802.15.4 compliance [18]. The CC2420 is controlled by the TI MSP430 microcontroller through the SPI port and a series of digital I/O lines and interrupts (see the Schematics on page 7 for more information). The radio may be shut off by the microcontroller for low power duty cycled operation. The CC2420 has programmable output power. The CC2420 provides a digital received signal strength indicator (RSSI) that may be read any time. Additionally, on each packet reception, the CC2420 samples the first eight chips, calculates the error rate, and produces a link quality indication (LQI) value with each received packet.

The M25P40 is a 4 Mb (512K x 8) Serial Flash Memory, with write protection mechanisms, accessed by a high speed SPI-compatible bus. The memory can program 1 to 256 bytes at a time, using the Page Program instruction. The memory is organized as 8 sectors, each containing 256 pages. Each page is 256 bytes wide. Thus, the whole memory can be viewed as consisting of 2048 pages, or 524,288 bytes. The whole memory can be erased using the Bulk Erase instruction or a sector at a time using the Sector Erase instruction.

Each sensor node should have a unique identification, such as a number. A software solution is to write a number in the memory device at the programming phase. Although this is an option, a hardware solution is more elegant. Dallas Semiconductor devices, such as DS2401, offer a unique ROM code that contains a 64-bit number.

It is desired to know the time when an event happens, like keeping record when a sensor signal was read. Adding a real-time clock allows the sensor node to time and date stamp, or create a logbook. It is also possible to create a real-time clock with the microcontroller, but it is also desired to put the microcontroller in the low-power mode to save energy. This solution would make the software very complex. A more simple approach is to add a real-time clock. The DS2417 time chip offers a simple solution for storing and retrieving vital time information with minimal hardware. It uses the 1-Wire protocol, thus, only one pin is required for communication with the device.

The Fractus 50Ω single-ended Compact Reach XtendTM chip antenna is selected to ensure high performance, minimal power consumption and small dimensions for the node platform. The Fractus® Compact Reach XtendTM chip antenna is engineered specifically for devices operating at 2.4 GHz. The Compact Reach XtendTM chip antenna uses space-filling properties of fractal technology to minimize its size while maintaining a high radiation efficiency value. This directly impacts antenna reliability in achieving a greater communication range (distance) and in improving battery life. More than 50% of the power delivered to the antenna is being transmitted to the free space. This is a very high value that will increase communication reliability and prolong the battery life.

The expansion connector provides various interfaces, such as USART (UART/SPI/I2C), analog-to-digital conversion, general digital I/O, pulse width modulation output, programming interface(JTAG and Bootstrap loader). This makes it available to integrate a variety of physiological sensors or actuators.

2.3.2 Results

WBSN node platform

The WBSN node platform, also named as MediMesh mote, has a size of 26*23mm, as in

Figure 2-4. It is ideal to be employed as a platform for developing wearable biosensors. In addition, the stackable design of the WBSN node and the available interface channels ease the integration of different sensors with the WBSN node. The WBSN node can significantly cut the development cycle for wireless biosensor development.

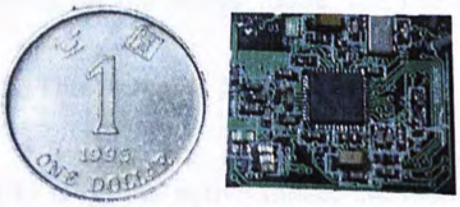


Figure 2-4: WBSN node platform (MediMesh mote).

Power budget

The power budget of each separate part of the node is listed in Table 2-1[19].

Mode	Current
Microcontroller (1.8-3.6) V	
Down	0.1μA
Idle	1.3μA
Active	400μA
Radio (2.1 -3.6) V	
Down	20μA
Transmit	19.7mA
Receive	17.4mA
Memory (2.7-3.6)V	
Down	10μA
Standby	50μA
Read	4mA
Write	15mA
Real-Time Clock (2.5-5.5)V	
Active	0.200μA

Table 2-1: Node power budget

In this section, we assume the node platform operates on 3V. The WBSN node will be usually in one of the following states:

Down mode - everything is turned off and the MCU is on the LPM3 operating mode. The current is 10.5μA and the power is 31.5μW.

Receive mode - the MCU is on the active mode, the radio is on receive mode and everything else is turned off. The current is 17.8mA, the power is 53.4mW.

Transmit mode - the MCU is on the active mode, the radio is on transmit mode and everything else is turned off. The current is 20.1mA, the power is 60.3mW.

Memory reading - the MCU is on the active mode, the memory is on reading mode and everything else is turned off. The current is 4.4mA, the power is 13.2mW.

Memory writing - the MCU is on the active mode, the memory is on writing mode and everything else is turned off. The current is 15.4mA, the power is 46.2mW.

Sensing mode - the MCU is on the active mode, a specific sensor is on and everything else is turned off. This mode is dependent on which sensor device is being used.

To evaluate the performance of the WBSN node, we define an application scenario. In this scenario, the node acts as a repeater, keeping a log of events. It operates for 1% of the time. In this period, it tries to receive packet 3/4 of this period and transmits in 1/4 of this period. It writes to external memory using 1/4 period and also reads the external memory

1/4 of the time to save the received packets and keep consistency of data. It does not use the sensors. Table 2-2 shows the lifetime (in number of months) for each scenario and platform, depending on the battery type capacity.

	Current(mA)	Duty cycle (%)	Computed mA-hr
Processor			
current active	0.4	1	0.005287
current sleep	0.0013	99	
Radio			
current in receive	17.4	0.75	0.19955
current transmit	19.7	0.25	
current sleep	0.02	99	
Logger Memory (max)			
Write	15	0.25	0.05745
Read	4	0.25	
Sleep	0.01	99.5	

Table 2-2: Computed mA-hr.

So the total average current is about 0.2623mA. If a battery with capacity of 250mA-hr is employed as the power, the node without sensor can work for about 40 days.

2.3.3 Conclusion

The proposed and implemented WBSN node platform serves as a research platform for study and evaluation of wireless biomedical sensor networks. The main features of the realized WBSN node include:

- Miniature and light weighted- a wearable device.
- Low-power - a long term monitoring device.
- Flexible - a research platform.

2.4 Software design

2.4.1 TinyOS

The system software is implemented in a TinyOS environment [20]. TinyOS is a lightweight open source operating system for wireless embedded sensors. It is designed to use minimal resources, and its configuration is defined at compile time by combining components from the TinyOS library and custom-developed components. A TinyOS application is implemented as a set of component modules written in nesC [21]. The nesC language extends the C language with new constructs to facilitate the component architecture and multitasking. By adding direct language support for task synchronization and task management, it allows rapid development and minimizes resource usage.

2.4.2 Software Organization

Figure 2-5 shows generalized software architecture, and from left to right, it shows the network coordinator software, WBSN node's software, and daughter sensor board software.

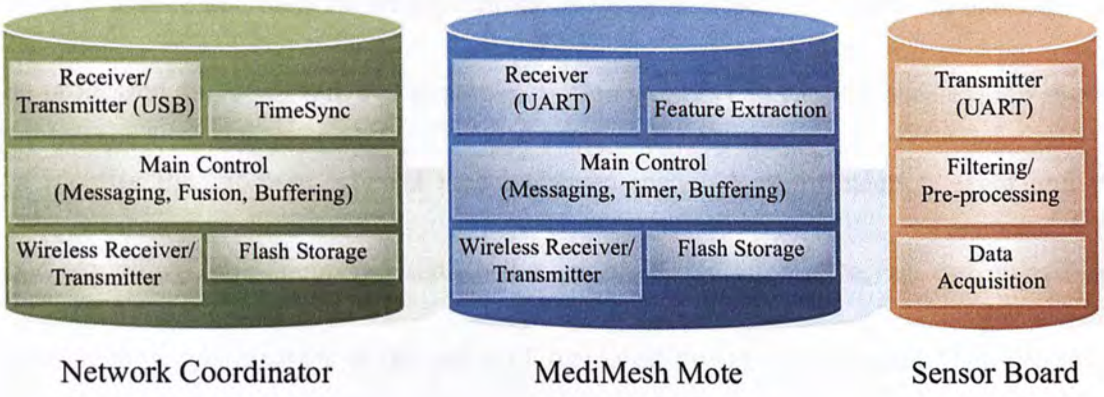


Figure 2-5: Software architecture.

Network Coordinator: The network coordinator is also implemented on a MediMesh mote platform. It feeds the personal station (PS) application through its USB connector and manages the WBSN -- transmits the messages from the PS that establish a session, assigns the individual sensor ID, distributes keys if secure data are encrypted, and assigns communication slots. The network coordinator autonomously emits beacon messages for time synchronization. After the initial setup, it receives data from individual sensors, aggregates the data, and forwards it to the PS application.

MediMesh Mote: The mote software is implemented as multiple TinyOS components encompassing the following high-level functions: wireless communication, extended flash storage, messaging software, board-to-board communications, and signal feature extraction. MediMesh mote serves as a master controller, and it requests data from the daughter sensor board by raising an interrupt request line. The daughter sensor board sends preprocessed data via an asynchronous serial interface. The received data can also be processed and analyzed. For example, motion sensors can analyze acceleration signals to identify the moment when a step has been made. A step detection event and the corresponding time stamp are sent to the server. As an alternative, we can upload raw data from accelerometers at the price of increased power consumption. The processed data set can be stored in an external serial flash memory in the case of autonomous operation or if the wireless channel is not available. It should be noted that the flash memory, CC2420 radio interface, and the daughter sensor board all share a single serial interface of the MSP30 on the node platform. This presented its own set of challenges since the node platform is tasked with reliable communications to multiple devices using this single serial interface. For example, to communicate with the daughter card, the software must configure the serial interface as a UART running at 115.2 kbps. Once sensor data is received, the serial interface is dynamically reconfigured for SPI at 500 kbps, allowing communications to both the on-board radio and flash. Because events are recognized asynchronously, accurate event time stamps can be made, but often the messages must be buffered and queued for transmission when the serial interface is available.

Sensor Software: The sensor boards handle acquisition of physiological signals and preprocessing. For example, the motion analysis sensor board samples three independent accelerometer axes each at a rate of 200 Hz. The raw accelerometer data is filtered and preprocessed. The filtering includes moving an average filter to eliminate high frequency movement artifacts, and separation of low and high frequency components of the acceleration signal. Sensor orientation can be calculated as the angle between low frequency accelerometer components. User activity is estimated with a function based on the sum of the integrals of the AC components in each channel.

Chapter 3 Wireless Medical Sensors

This chapter describes the various sensors which have been implemented. We categorize the sensors into three groups: (1) User state component: pulse oximetry, electrocardiograph, and galvanic skin response. (2) Location tracking componential: outdoor location tracking and indoor location tracking. (3) User activity component: motion tracking.

3.1 Sensing Physiological Information

3.1.1 Pulse Oximetry

As a demonstration of wireless vital sign monitoring using sensor network devices, we have developed a mote-based pulse oximeter, Pulse oximetry has been in use as a medical diagnostic technique since its invention in the early 1970s [22]. This non-invasive technology is used to reliably obtain two key patient health metrics: heart rate (HR) and blood oxygen saturation (SaO_2). These two parameters yield critical information, particularly in emergencies when a sudden change in the heart rate or reduction in blood oxygenation may indicate a need for urgent medical response. This type of monitoring is especially useful for new born infants and during surgery. Pulse oximetry can provide advance warning of the onset of hypoxemia even before the patient manifests physical symptoms.

In a pulse oximeter, the calculation of the level of oxygenation of blood is based on measuring the intensity of light that has been attenuated by body tissue. SaO_2 is defined as the ratio of the level oxygenated Hemoglobin (HbO_2) over the total Hemoglobin level(Hb) [23]:

$$SaO_2 = \frac{HbO_2}{Hb}$$

Body tissue absorbs different amounts of light depending on the oxygenation level of blood that is passing through it. This characteristic is non-linear. Two different wavelengths of light are used; each is turned on and measured alternately. By using two different wavelengths, the mathematical complexity of measurement can be reduced.

$$R' = \frac{\log(I_{ac})\lambda_1}{\log(I_{ac})\lambda_2} SaO_2 R$$

There are a DC and an AC component in the measurements. It is assumed that the DC component is a result of the absorption by the body tissue and veins. The AC component is the result of the absorption by the arteries.

In practice, the relationship between SaO_2 and R is not as linear as indicated by the above formula. For this reason a look up table is used to provide a correct reading.

Pulse oximetry involves the projection of infrared and near infrared light through blood vessels near the skin. Pulse oximeter typically incorporates a plastic housing that slips over the index finger or earlobe. The housing contains an array of LEDs along one inner surface and an optoelectronic sensor opposite. By detecting the amount of light absorbed by hemoglobin in the blood at two different wavelengths (typically 650nm and 805nm), the level of oxygen saturation can be measured. In addition, heart rate can be determined from the pattern of light absorption over time, since blood vessels contract and expand with the patient's pulse. Computation of HR and SpO_2 from the light transmission waveforms can be performed using standard digital signal processing (DSP) techniques. Sophisticated algorithms have been developed to mitigate errors due to motion artifacts.

Circuit Design

This section demonstrates the implementation of a portable pulse oximeter using the ultra low power capability of the MSP430 microcontroller. Because of the high level of analog integration of MSP430, the external components can be kept to a minimum. Furthermore, by keeping ON time to a minimum and power cycling the two light sources, power consumption is reduced.

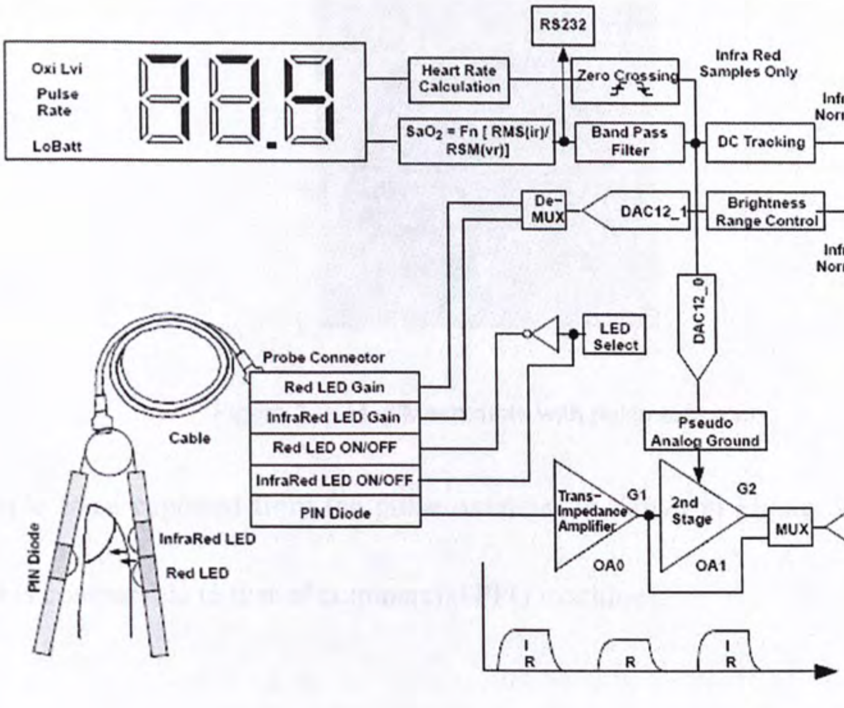


Figure 3-1: Pulse oximeter block diagram [24].

The two LEDs are time multiplexed at 500 times per second. The PIN diode is therefore alternately excited by each LED light source. The PIN diode signal is amplified by the built in operational amplifiers OA0 and OA1. The ADC12 samples the output of both amplifiers. The samples are correctly sequenced by the ADC12 hardware and the MCU software separates the infra-red and the red components. Apart from the MCU and four transistors, only passive components are needed for this design. The pulse oximeter connected with the MediMesh mote is shown in Figure 3-2.

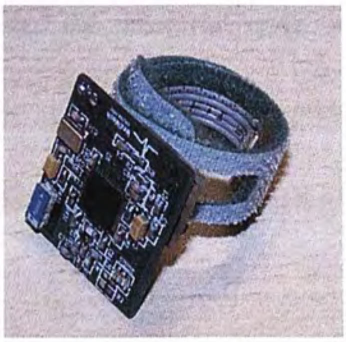


Figure 3-2: MediMesh mote with pulse oximeter.

A sample trace captured from the pulse oximeter is shown in Figure 3-3. The circuit's output is comparable to that of commercial PPG machines.

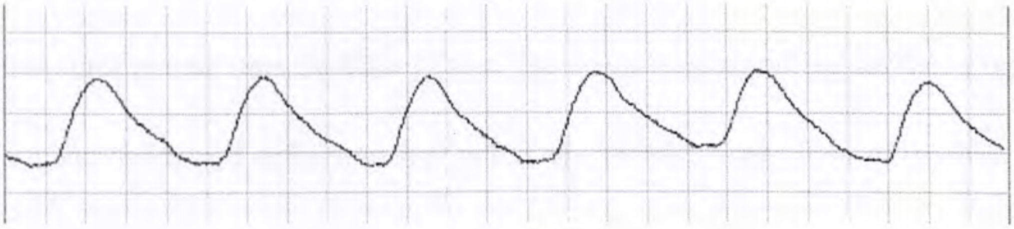


Figure 3-3: A sample trace captured from our pulse oximeter.

3.1.2 Electrocardiograph

An electrocardiogram (ECG or EKG) is a graphic tracing of the voltage generated by the cardiac or heart muscle during a heartbeat [25][26]. It provides very accurate evaluation of the performance of the heart. The heart generates an electrochemical impulse that spreads out in the heart in such a fashion as to cause the cells to contract and relax in a timely order and, thus, give the heart a pumping characteristic. This sequence is initiated by a group of nerve cells called the sinoatrial node, resulting in a polarization and depolarization of the cells of the heart. Because this action is electrical in nature and the body is conductive with its fluid content, this electrochemical action can be measured at the surface of the body.

An actual voltage potential of approximately 1 mV develops between various body points. This can be measured by placing electrode contacts on the body. The four extremities and the chest wall have become standard sites for applying the electrodes. Standardizing electrocardiograms makes it possible to compare them as taken from person to person and from time to time from the same person. The normal electrocardiogram shows typical upward and downward deflections that reflect the alternate contraction of the atria (the two upper chambers) and of the ventricles (the two lower chambers) of the heart.

Two different types of electrocardiograph (EKG or ECG) are commonly used in clinical and trauma care to measure the electrical activity of the heart. The most prevalent EKG type involves the connection of between twelve and fifteen leads to a patient's chest, arms and right leg via adhesive foam pads. The device records a short sampling (not more than thirty seconds) of the heart's electrical activity between different pairs of electrodes. Each pair of leads provides a unique and detailed picture of the cardiac rhythm, an individual echo of the heart's electrical impulses as they are conducted through surrounding tissue. An experienced cardiologist can rapidly interpret a standard EKG tracing to diagnose a wide range of cardiac arrhythmias, as well as acute myocardial ischemia and infarction. However, because standard EKG traces only represent a short sampling of patient data, irregular or intermittent cardiac conditions may not be identifiable. To address this shortcoming, many hospitals also employ continuous EKG telemetry to monitor patients in intensive care. This involves the use of a two- or three-electrode EKG to evaluate a patient's cardiac activity for an extended period. The amplified heart signals are either displayed on a screen or printed onto a roll of paper adjacent to the patient's bedside. A physician may advise continuous monitoring if there is a chance that a patient has cardiac problems which occur intermittently, maybe only once or twice a day. Continuous telemetry may also be useful as a means of alerting healthcare staff to the first signs of deterioration of a patient's condition.

Circuit Design

EKG systems operate by acquiring and amplifying the electrical signals generated with each contraction and expansion of the cardiac muscle. Commercial systems generally incorporate one or more instrumentation amplifiers with excellent common mode noise rejection and signal amplification characteristics. In addition, such systems may include dedicated signal processing circuitry to further enhance the quality of the tracing. Many EKG machines, both standard and continuous, are marketed as "portable" but this does not necessarily mean that they are small and unobtrusive. Most such appliances receive power from an electrical outlet and are sufficiently heavy that they must be mounted on a cart and wheeled from one location to the next.

We have developed sensor boards for the MediMesh mote platforms that provide continuous EKG monitoring (Figure 3-4) [27], according to TI's solution.

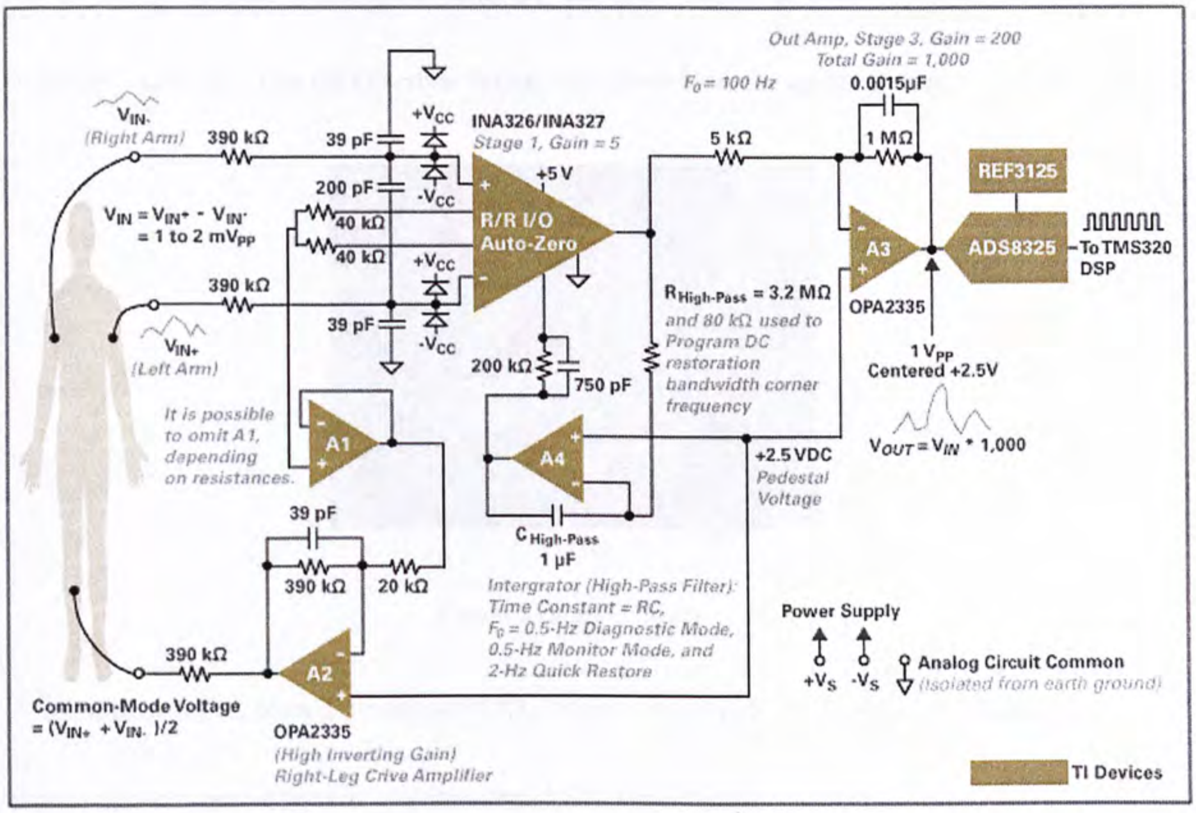


Figure 3-4: ECG circuit.

The circuit design incorporates the Texas Instruments INA326 CMOS instrumentation amplifier. The circuit draws power from the mote's battery pack. Connectors are provided to three leads that attach to the patient's upper and lower chest; one lead serves to properly bias the patient's skin while the other two are used to measure cardiac activity. The INA326 amplifies the differential signal by a factor of 5 and filters out almost all common-mode noise. A high-pass feedback filter dynamically corrects any DC shift that may occur over time. The signal subsequently passes to an op-amp that provides further amplification and acts as a low-pass filter. The resulting trace is routed to an ADC port on the mote. A TinyOS component samples the EKG signal at a configurable frequency (typically 120 Hz). The EKG sensor board with three leads is shown in Figure 3-5.

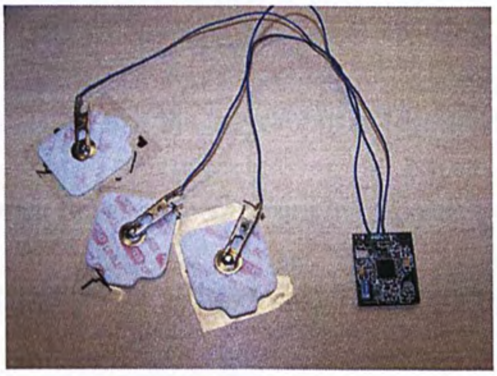


Figure 3-5: ECG Signal.

A sample trace captured from our EKG sensor is shown in Figure 3-6. The circuit's output is comparable to that of commercial EKG machines.

Figure 3-6: Sample EKG trace captured from our EKG sensor.

3.1.3 Galvanic Skin Response

Galvanic skin response (GSR) is a term which is often used to describe the electrical activity which gives evidence of psycophysiological changes. Electrodermal Response (EDR) is a broader term used by the psychophysiology community to describe the changes which take place on the stratum corneum in response to the sympathetic nervous system. It is thought that the autonomic functions of the brain control the output of sweat glands and that electrodermal activity varies with psychological changes like increased arousal and anxiety.

GSR is often measured using a bipolar electrode placement of on the medial phalanx. A sophisticated design was developed by Blake Brasher. This design made use of a pair of Op Amps: one to buffer and a second to serve as a non-inverting amplifier.

A design by Brian McDonald of the Mindgames group provides a much more sophisticated GSR amplifier, but also introduces a Butterworth low-pass filter to address aliasing and noise issues. This is the current design used.

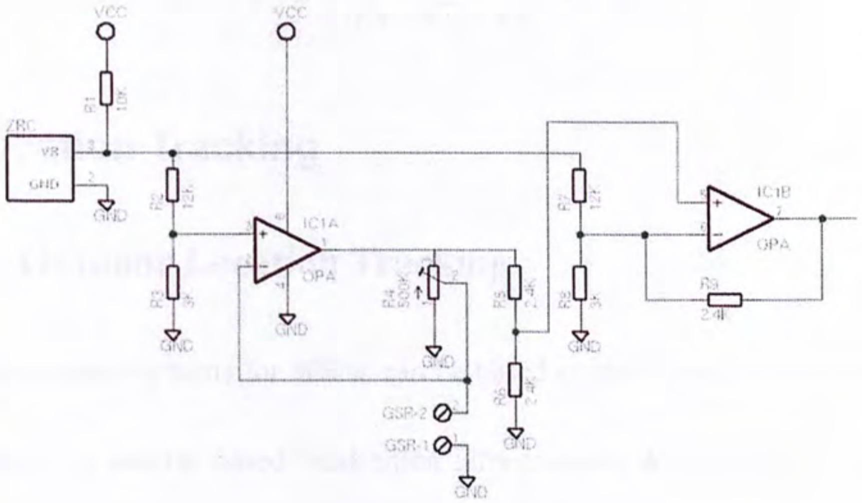


Figure 3-7: GSR circuit.

The design operates as follows. A voltage divider (R1-R2) provides a 2V supply for two voltage dividers (R4- R5 and R9-R10). The first of these provides a 0.5 voltage reference to an LT1014/LT precision op amp (IC1A). This non-inverting amplifier has a 40K resistor to provide gain (R6) and connectors through the skin electrodes to ground (X1-1, X1-2). Its output is V1out=1+R6/Rskin. The capacitor (C1) stabilizes the circuit by acting like a short circuit for high frequencies. The output of this amplifier is then fed into a voltage divider (R7-R8) which is part of the differential amplifier that is the second stage of the signal conditioning circuit. This signal is then fed to into the positive terminal of another LT1014/LT op amp (IC1B). The negative terminal is fed a reference signal of

0.5 V. The output of this amplifier is

$$V2_{out} = V2 \times \frac{(R11 + R9) \times R8}{(R8 + R7) \times R9} - V1 \times \frac{R11}{R9}$$

3.2 Location Tracking

3.2.1 Outdoor Location Tracking

Outdoor localization systems for WSNs can be based on the Global Positioning System (GPS), which is a satellite-based localization infrastructure. At any location on earth, a GPS-receiver can be localized using information of at least four GPS satellites. The receiver computes the time-of-light of the different satellite signals as the difference between its local time and the time the signals were sent and converts the times into distance estimates. The receiver also determines the satellites' locations from their radio signals and an internal satellite database. From this knowledge, the receiver's position is derived, generally with an accuracy of about ten meters. GPS can easily be used in sensor networks, by equipping the sensor nodes with GPS-receivers.

Nevertheless, GPS-based localization in sensor networks has some disadvantages. The first problem is that a GPS-receiver consumes a lot of energy, which is known to be a scarce resource on a sensor node. The next problem relates to radio signal propagation in an indoor environment: walls, doors and furniture can disturb or even entirely block the satellite signals. It is often a problem to even detect four satellite signals in an indoor environment. In any case, bad distance estimates result and therefore localization errors are large indoors. A final disadvantage is the high price for equipping all nodes in a network with expensive GPS-receivers.

3.2.2 Indoor Location Tracking

Localization in sensor networks can be achieved using knowledge about the radio signal behavior and the reception characteristics between two different sensor nodes [28][29]. The quality of a radio signal, i.e. its strength at reception time, is expressed by the radio signal strength indicator (RSSI): the higher the RSSI value, the better the signal reception. The main advantage of using radio-based localization techniques is that no additional hardware for the sensor nodes is required. The main disadvantage of the technique is that the measured signal strengths are generally unstable and variable over time, which leads to localization errors. In this section, two common localization techniques using radio signal strength information are presented.

Converting Signal Strength to Distance

In theory, there exists an exponential relation between the strength of a signal sent out by a radio and the distance the signal has travelled. In reality, this correlation has proven to be less perfect, but it still exists. The relation forms the basis for the first RSSI-based localization technique. Anchors broadcast their position at regular intervals. Unknown nodes receive the message and measure the strength of the received signal. This signal strength is converted to a distance estimate, using the exponential relation. Trilateration is used to convert the distance estimate between anchor and unknown node into coordinates for the latter. Localizations errors for this method range from two to three meters at average, with indoor errors being larger than outdoor ones. The main reason for the large errors is that the effective radio-signal propagation properties differ from the perfect theoretical relation that is assumed in the algorithm. Reflections, fading and multipath effects largely influence the effective signal propagation. The distance estimates, which are based on the theoretical relation, are thus inaccurate and lead to high errors in the calculated locations.

Fingerprinting Signal Strengths

The second method that uses RSSI for localization is called fingerprinting. This technique is based on the specific behavior of radio signals in a given environment, including reflections, fading and so on, rather than on the theoretical strength-distance relation. The fingerprinting technique is an anchor-based technique that consists of two separate phases. During the first phase, called the offline phase, a fingerprint database of the environment is constructed. A node is put at a number of predefined points in the deployment area to record the fluctuations in signal strength at these specific points. At each location, the node sends a number of messages and all anchors measure the signal strength of the received messages, or the other way around. The combination of the RSSI-values measured by the different anchors when the node is at a certain location forms the fingerprint of this location: a series of RSSI-values that are representative for that particular location. Per location, a number of fingerprints are stored in a database, needed by the second phase. During the next phase, called the online phase, real-time localization is performed. An unknown node has to be localized in the deployment area. The unknown node broadcasts a message at regular intervals and the anchors measure the signal strength upon reception of a message. The measured RSSI-values are combined into a RSSI-sample. Afterwards, the best matches between the values in the RSSI-sample and the values stored in the database are searched for. The resulting matches determine the final position of the unknown node. Its location could either be the value of the closest match or an average of a few best matches. The specific algorithm used for matching is not relevant here. The main advantage of using RSSI this way is that the unpredictable RSSI variations in space are handled, which makes the approach a little more accurate. Errors using this method are reduced to an average of one to two meters. The greatest disadvantage of the method is that an offline phase is required for the system to work. The offline phase is in the first place very time consuming. Moreover, the fingerprinting database that is created during the offline phase is location dependent. If one wants to use the same system in another environment or if radical changes to the current environment are made, the offline phase has to be repeated.

Tracking patients and rescue personnel is an important wireless technologies application in disaster response. For example, in a mass casualty incident, you can place tractable vital sign sensors on many patients. This lets you quickly locate a patient who suddenly requires immediate attention—an essential part of a successful triage. Firefighters entering a large building often cannot see because of heavy smoke coverage and have no a priori notion of building layout. By installing wireless, battery operated RF beacons in a building in advance of a fire, firefighters and rescuers could use a heads-up display to track their location and monitor safe exit routes. Likewise, an incident commander could track multiple rescuers' locations in the building from the command post. Such capabilities would have greatly improved rescue operations on 11 September 2001. The indoor location system, based upon the MoteTrack [17] project developed at Harvard University, is specifically designed for disaster response. It operates using the low-power, single-chip radio transceivers found in sensor network nodes, which rescue personnel can easily wear or embed in wearable vital sign sensors. MoteTrack operates in an entirely decentralized, robust fashion, providing good location accuracy despite partial failures of the location- tracking infrastructure. With MoteTrack, you populate a building or other area with a number of beacon nodes, which can operate off battery power or use main power with a battery backup. These beacon nodes can replace existing smoke detectors and serve as both wireless smoke detectors and location trackers. If the nodes track location infrequently, such as only in an emergency, and with careful duty cycling, the operation lifetime of beacon nodes running off batteries will resemble that of a battery-operated smoke detector. MoteTrack doesn't require additional hardware beyond the sensor node's radio and microprocessor. Beacon nodes broadcast periodic beacon messages that consist of a tuple of the format {sourceID, powerLevel}. sourceID is the unique identifier of the beacon node, and powerLevel is the transmission power level used to broadcast the message. Each mobile node that wants to use MoteTrack to determine its location listens for some period of time to acquire a signature. A signature consists of the beacon messages received over some time interval along with the received signal strength indication for each transmission power level. Finally, we define a reference signature as a signature combined with a known 3D location (x, y, z). MoteTrack uses a two-phase process to estimate locations: an offline collection of reference signatures followed by online location estimation. Once you've installed the beacon nodes, you use a mobile node to acquire a reference signature set at known, fixed locations throughout the building. Afterwards, a mobile node can obtain a signature and send it to the beacon node from which it received the strongest RSSI to estimate its location. This approach resembles 802.11-based location-tracking systems, such as

RADAR. However, unlike RADAR, MoteTrack is completely decentralized— that is, it runs entirely on small, low-power sensor nodes and doesn't require a back-end database to store reference signatures or perform location calculations. MoteTrack carefully replicates its reference signature set across beacon nodes such that each beacon node stores only a subset of all reference signatures. The beacon nodes themselves perform all data storage and computation using only the locally stored reference signatures. MoteTrack achieves a high level of robustness to beacon node failure through its distributed architecture and by using an adaptive algorithm for estimating locations that is a function of the percent of locally failed beacon nodes. The high level of robustness to failure is an important factor for disaster response applications.

3.3 Motion Tracking

Apart from traditional vital sign monitoring, sensor networks can be used in specific clinical studies that may require specialized instrumentation to record physiological signals of interest [30][31][32]. There are two main studies involving motion analysis. The first focuses on patients undergoing physical rehabilitation after stroke while the second aims to evaluate the effectiveness of treatments for Parkinson's disease. Both studies require capturing detailed data on muscular activity and on limb movements.

Stroke is a form of brain damage caused either by internal bleeding or by an acute lack of blood in some part of the brain. In either case, the function of a part of the brain is temporarily or permanently stopped. A recovering stroke patient may experience impaired movement and weakness of one half of the body, in addition to speech problems and difficulty maintaining a sense of balance.

Parkinson's disease is a degenerative brain disorder that typically develops after the age of 50. The characteristic symptom of Parkinson's is an involuntary and uncontrollable shaking that usually starts in the hands but which, if left untreated, can eventually spread throughout the body. In many cases the cause is unclear, but Secondary Parkinson's Disease may be triggered by conditions such as brain injury or certain brain infections. More accurate measurement of motor fluctuations during daily life would benefit patients by enabling doctors to fine-tune the dosage and timing of existing medication. It would also help researchers to better evaluate new therapies in clinical trials.

3.3.1 Technology

Traditional motion-capture systems use a wired data logger carried in a waist harness; a multitude of wires runs from the harness to various sensors positioned on body segments of interest (typically the arms, legs, back and torso). Clearly, the use of wearable wireless sensors would greatly simplify data collection and would allow patients to wear the sensors for longer periods of time since the bulky data logger and leads would be eliminated. Three sensor types are commonly used for motion analysis studies in the field: accelerometers, gyroscopes, and surface electrodes for electromyogram (EMG) recordings. Triaxial accelerometers measure the orientation and movement of each body segment. Gyroscopes measure angular velocity and combined with accelerometer data can be used to accurately determine limb position. Surface EMG electrodes capture the electrical field generated by depolarized zones traveling along the muscle fibers during a muscle contraction. The root mean square value of the EMG data is roughly proportional to the force exerted by the monitored muscle. Thus analysis of the patterns of EMG activity can lead to the identification of motor tasks and their characteristics.

3.3.2 Motion Analysis Sensor Board

Our motion analysis sensor board (Figure 1(c)) interfaces to the MediMesh mote and incorporates two 2-axis accelerometer (ADXL232) mounted in a triaxial configuration. The board includes a number of operational amplifiers to enhance signal quality together with voltage conditioning ICs to power passive filters to eliminate noise. Signals are routed through the board to ADC ports on the MediMesh mote. This is a prototype design and the next revision will include three gyroscopes mounted in a triaxial configuration and EMG unit. In our proposed studies, a patient will wear several MediMesh motes outfitted with a motion analysis sensor board, one on each body segment of interest. In the stroke patient study, this will require one node on each of the upper arm, lower arm, back, and torso on the patient's affected side. The battery pack will be replaced with a thin, rechargeable battery which significantly reduces size and weight. Each axis of the accelerometers and gyroscopes is sampled at 100 Hz while the EMG is sampled at 1 kHz. Data is captured to the mote's EEPROM and relayed using a reliable communication protocol to a nearby base station for logging. Because it is necessary to correlate signals across multiple sensor devices, data from each node needs to be consistently time stamped. We are investigating various time synchronization techniques for this purpose.

3.4 Discussions

In a wireless wearable sensor network, different sensors need to be placed in different locations in order to acquire the desired signals. Once the placement has been fixed, two system architecture issues remain to be resolved: (1) communication/computation tradeoffs for the whole sensor network and (2) The network architecture and transmission technology. Both issues are determined by the same criteria: system power consumption and user comfort.

Sensor Placement Constraints - The placement of the sensors is dictated by tradeoff between two considerations: the quality of the signal received in particular location and ergonomic concerns. The pulse and GSR sensors need to be placed in contact with the skin. In addition, the GSR sensors have been found to produce good results on fingers, palms and feet only. A good choice is to put the GSR electrodes as rings on the fingers and the pulse sensor on the wrist.

Ideally, to provide detailed description of the user's posture and body motion at least one 3-axis accelerometer should be placed on each side of every relevant joint. In practice, placing one sensor on relevant body parts should be sufficient for most purposes. This includes the upper and lower legs and arms, shoulders, and the torso.

Computation and Communication Considerations - In simplest architecture, the raw data generated by each sensor would be sent directly to central module. However, distributed approach has several advantages. For one it is often more power efficient to perform parts of the feature extraction locally than to transmit large amounts of raw data. In addition to power considerations, higher data rates require more cumbersome transmission systems. Finally, by combining data from physically adjacent analogically related sensors the overall number of long links crossing clothing and body parts boundaries can be reduced. Further improvements can be obtained by combining such sensors into modules sharing computing resources. Useful features require filtering, spectral analysis and simple statistical parameterization. In particular, for the acceleration performing such operations locally has proven advantageous. For the acceleration sensor, network hierarchical topology following the body anatomy is necessary.

Chapter 4 Applications in Medical Care

4.1 Introduction

The ability to augment medical telemetry with tiny, wearable, wireless sensors would have a profound impact on many aspects of clinical practice. Wireless medical telemetry, emergency medical care, triage, and intensive care can all benefit from continuous vital sign monitoring, especially immediate notification of patient deterioration. Sensor data can be integrated into electronic patient care records and retrieved for later analysis. In a wide range of clinical studies, especially those involving ambulatory or at-home monitoring, wireless sensors would permit data acquisition at higher resolution and for longer durations than existing monitoring solutions.

Wireless medical telemetry is not altogether new. A number of wireless medical monitors are currently on the market, including electrocardiographs (EKGs), pulse oximeters, blood pressure monitors, and fetal heart rate and maternal uterine monitors. Most of these devices use Bluetooth or the analog Wireless Medical Telemetry Service (WMTS) bands, although several employ IEEE 802.11. However, these systems are generally designed only to “cut the cord” between the sensor worn by the patient and a bedside monitor or other nearby receiving device. They are not intended to participate in a network, to relay data to multiple receivers (e.g. by means of multi-hop routing), or to scale to large numbers of monitors in an area. In addition, few of these systems are designed to be wearable; most remain attached to the hospital bed, and the few wireless ambulatory products on the market are generally large and cumbersome. As an example, the Welch-Allyn Micropaq monitor [33] measures over 18 cm × 8.8 cm × 4cm and weighs nearly half a kilogram. The emergence of low-power, single-chip radios based on the Bluetooth and 802.15.4 standards has precipitated the design of small, wearable, truly networked medical sensors. In a mass casualty or disaster setting, medics can place tiny sensors on each patient to form an ad hoc network, relaying continuous vital sign data to multiple receiving devices (e.g. PDAs carried by physicians, or laptop base stations in ambulances). In addition to relaying vital sign data, each node can act as an "active triage tag," storing information about the wearer (identification, medical history, severity status, etc.) RF-based localization can be used to track patient and first responder location on the scene. Such a system can be translated directly into hospital settings where wired monitoring is cumbersome (especially with pediatric and neonatal patients) and obstructs the caregiver's access to the patient. The requirements for a medical sensor network design depend greatly on the specific application and deployment environment. A sensor network designed for ad hoc deployment in an emergency situation has very different requirements than one deployed permanently in a hospital. For example, the latter can make use of fixed, powered gateway nodes which provide access to a wired network infrastructure.

In this chapter, we will discuss two important application scenarios of wireless biomedical sensor network: wearable wireless body area network and application in emergency medical care and disaster response.

4.2 Wearable Wireless Body Area Network

Wearable systems for continuous health monitoring are a key technology in helping the transition to more proactive and affordable healthcare [34][35]. Wearable health monitoring systems allow an individual to closely monitor changes in her or his vital signs and provide feedback to help maintain an optimal health status. If integrated into a telemedical system, these systems can even alert medical personnel when life-threatening changes occur. In addition, patients can benefit from continuous long-term monitoring as a part of a diagnostic procedure, can achieve optimal maintenance of a chronic condition, or can be supervised during recovery from an acute event or surgical procedure. Long-term health monitoring can capture the diurnal and circadian variations in physiological signals. These variations, for example, are a very good recovery indicator in cardiac patients after myocardial infarction [36][37]. In addition, long-term monitoring can confirm adherence to treatment guidelines or help monitor effects of drug therapy. Other patients can also benefit from these systems; for example, the monitors can be used during physical rehabilitation after hip or knee surgeries, stroke rehabilitation, or brain trauma rehabilitation. A number of physiological sensors that monitor vital signs, environmental sensors (temperature, humidity, and light), and a location sensor can all be integrated into a Wearable Wireless Body Area Network (WWBAN) [38][39]. The WWBAN consisting of inexpensive, lightweight, and miniature sensors can allow long-term, unobtrusive health monitoring with instantaneous feedback to the user about the current health status and real-time or near real-time updates of the user's medical records. Such a system can be used for computer-supervised rehabilitation for various conditions, and even early detection of medical conditions. For example, intelligent heart monitors can warn users about impeding medical conditions or provide information for a specialized service in the case of catastrophic events. Accelerometer-based monitoring of physical activity with feedback can improve the process of physical rehabilitation [40]. When integrated into a broader telemedical system with patients' medical records, the WWBAN promises a revolution in medical research through data mining of all gathered information. The large amount of collected physiological data will allow quantitative analysis of various conditions and patterns. Researchers will be able to quantify the contribution of each parameter to a given condition and explore synergy between different parameters, if an adequate number of patients is studied in this manner.

4.2.1 Architecture

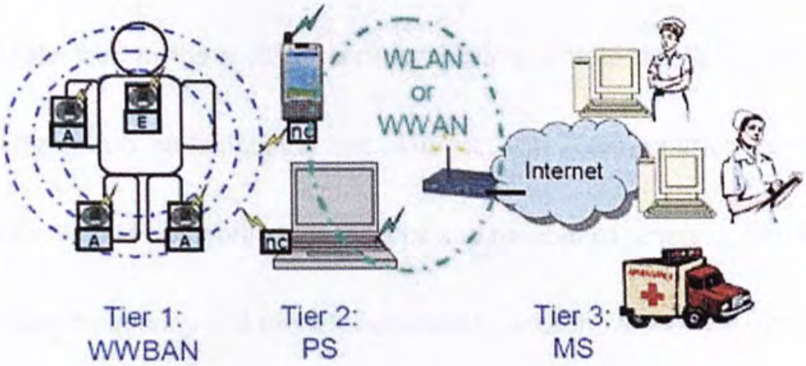
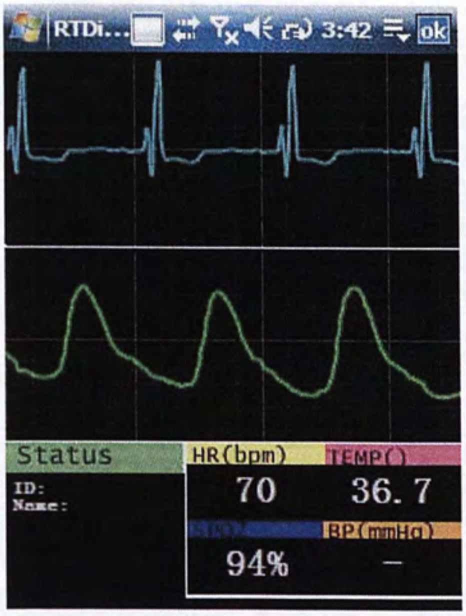


Figure 4-1: Wearable wireless body area network.

WWBANs are a pivotal part of a multi-tier telemedicine system as illustrated in Figure 4-1.Tier 1 encompasses a number of wireless medical sensor nodes that are integrated into a WWBAN. Each sensor node can sense, sample, and process one or more physiological signals. For example, an electrocardiogram sensor (ECG) can be used for monitoring heart activity, an electromyogram sensor (EMG) for monitoring muscle activity, an electroencephalogram sensor (EEG) for monitoring brain electrical activity, a blood pressure sensor for monitoring blood pressure, a tilt sensor for monitoring trunk position, and a breathing sensor for monitoring respiration; and motion sensors can be used to discriminate the user's status and estimate her or his level of activity.

Tier 2 encompasses the personal server (PS) application running on a Personal Digital

Assistant (PDA), a cell phone, or a home personal computer. A snapshot of the PDA-based PS application is show in Figure 4-2. The PS is responsible for a number of tasks providing a transparent interface to the wireless medical sensors, an interface to the user, and an interface to the medical server. The interface to the WWBAN includes the network configuration and management. The network configuration encompasses the following tasks: sensor node registration (type and number of sensors), initialization (e.g., specify sampling frequency and mode of operation), customization (e.g., run user-specific calibration or user-specific signal processing procedure upload), and setup of a secure communication (key exchange). Once the WWBAN network is configured, the PS application manages the network, taking care of channel sharing, time synchronization, data retrieval and processing, and fusion of the data. Based on synergy of information from multiple medical sensors the PS application should determine the user's state and his or her health status and provide feedback through a user-friendly and intuitive graphical or audio user interface. Finally, if a communication channel to the medical server is available, the PS establishes a secure link to the medical server and sends reports that can be integrated into the user's medical record. However, if a link between the PS and the medical server is not available, the PS should be able to store the data locally and initiate data uploads when a link becomes available.



HR(bpm) 70
TEMP() 36. 7
94%
BP(mmHg) –

Figure 4-2: A snapshot of the PDA-based PS application.

Tier 3 includes a medical server(s) accessed via the Internet. A snapshot of the medical server application is shown in Figure 4-3. In addition to the medical server, the last tier may encompass other servers, such as informal caregivers, commercial health care providers, and even emergency servers. The medical server typically runs a service that sets up a communication channel to the user's PS, collects the reports from the user, and integrates the data into the user's medical record. The service can issue recommendations, and even issue alerts if reports seem to indicate an abnormal condition.

Patient code: 401
Name: Arola
Sex: F
Doctor code: d_6
Room: 101
2006.5.3 16:44:18

Figure 4-3: A snapshot of the medical server application.

4.2.2 Deployment Scenarios

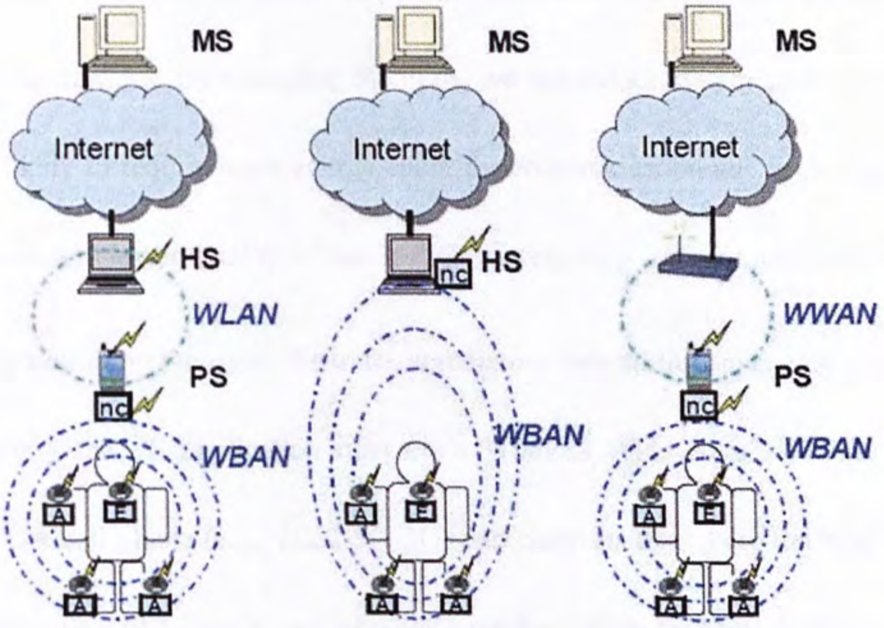


Figure 4-4: Deployment scenarios.

Figure 4-4 illustrates three typical scenarios using WWBAN. The configuration on the left can be deployed at home, in the workplace, or in hospitals. Wireless medical sensors attached to the user send data to a PDA, forming a short-range wireless network (e.g., IEEE 802.15.1 or 802.15.3/4). The PDA equipped with a WLAN interface (e.g., IEEE 802.11a/b/g) transmits the data to the home (central) server. The home server, already connected to the Internet, can establish a secure channel to the medical server and send periodic updates for the user's medical record.

The modified configuration in the middle is optimized for home health care. The sensor network coordinator (nc in Figure 2) is attached to the home personal server that runs the PS application. The medical sensor nodes and the network coordinator form a wireless personal area network. By excluding the PDA, we can reduce system cost. However, this setting is likely to require more energy spent for communication due to an increased RF output power and lower Quality of Service (QoS), requiring frequent retransmissions.

The configuration on the right illustrates ambulatory monitoring applicable any time and everywhere – the PS application runs on a Wireless Wide Area Network (WWAN) enabled PDA/cell phone (e.g., 2G, 2.5G, 3G) that connects directly to the medical server. To illustrate, we will follow a user who has a predisposition for heart disorders. The user continues his normal daily activities, but now equipped with several non-invasive medical sensors applied in his clothes or as tiny patches on his skin. The PS application can discriminate his state (walking, running, lying down, sitting, riding, etc) using the data from the motion sensors, and can recognize an arrhythmic event, analyzing the data from the ECG sensor. If his activity, heart rate, and personalized thresholds indicate an abnormal condition, he will receive a warning. In addition, a precise incident report can be sent to the medical server at the hospital or doctor's office.

4.3 Application in Ambulatory Setting

Wireless sensor networks have the potential to have enormous impact on many aspects of disaster response. Sensor devices can be used to capture continuous, real-time vital signs from a large number of patients, relaying the data to handheld computers carried by emergency medical technicians (EMTs), physicians, and nurses. Wearable sensor nodes can store patient data such as identification, history, and treatments, supplementing the use of back-end storage systems and paper charts. In a mass casualty event, sensor networks can greatly improve the ability of first responders to triage and treat multiple patients equipped with wearable wireless monitors. Such an approach has clear benefits for patient care but raises challenges in terms of reliability and complexity. Companies such as Nonin and Numed have developed wireless vital sign sensors based on Bluetooth technology. Other research projects include the European Commission's wide-ranging MobiHealth Project, which aims to provide continuous monitoring of patients outside the hospital environment by developing the concept of a 3G-enabled "Body-Area Network". The potential applications will save lives, create valuable data for medical research, and cut the cost of medical services.

4.3.1 Method

To demonstrate wireless sensor nodes' use in emergency case, we take advantage of two mote-based vital sign sensors: a pulse oximeter and a two lead electrocardiogram (EKG) sensor. The pulse oximeter captures a patient's heart rate and blood oxygen saturation

(SpO_2) by measuring the amount of light transmitted through a noninvasive sensor attached to the patient's finger. EMTs use these standard vital signs to determine a patient's general circulatory and respiratory status, which are among the first vital signs taken. Our mote-based pulse oximeter transmits the heart rate and SpO_2 data periodically (about once a second). Our mote-based EKG continually monitors the heart's electrical activity in more severely injured patients. For example, a patient with internal bleeding might require cardiac monitoring to determine that the heart rate and rhythm are within acceptable limits. You can use EKG signals to detect arrhythmia (abnormal heartbeat rhythm) or ischemia (lack of blood flow and oxygen to the heart), both of which point to potentially serious conditions. A custom-built circuit board attached to the MediMesh mote captures a trace of the heart's electrical signals through a set of leads attached to a patient's chest. The circuit board captures information at a rate of 120 Hz, compresses it using a differential encoding scheme, and transmits it via the mote's radio.

When faced with a large number of casualties, the goal is to first care for those patients who will benefit the most from trauma care and rapid surgical intervention. The system is designed to require little setup time. To accomplish this, EMTs can carry many mote packages and deploy them to monitor severely injured patients. Using sensors, triage in the field and triage at the hospital can be made interactive by continuously feeding patient capacity information from a sensor network to a decision support system. The same sensor network would track stable patients from triage, through treatment, to their final hospital destination, all the while conveying vital sign and location data to the host system.

4.3.2 The Software Architecture

Supporting the diverse requirements for medical sensor networks requires that we take a fresh look at the software environment, routing protocols, and query interfaces. We design the software architecture based on CodeBlue (Figure 4-5) [16], a protocol and middleware framework for medical sensor networks. CodeBlue is implemented in TinyOS and provides protocols for integrating wireless medical sensors and end-user devices such as PDAs and laptops. CodeBlue is intended to act as an "information plane" tying together a wide range of wireless devices used in medical settings.

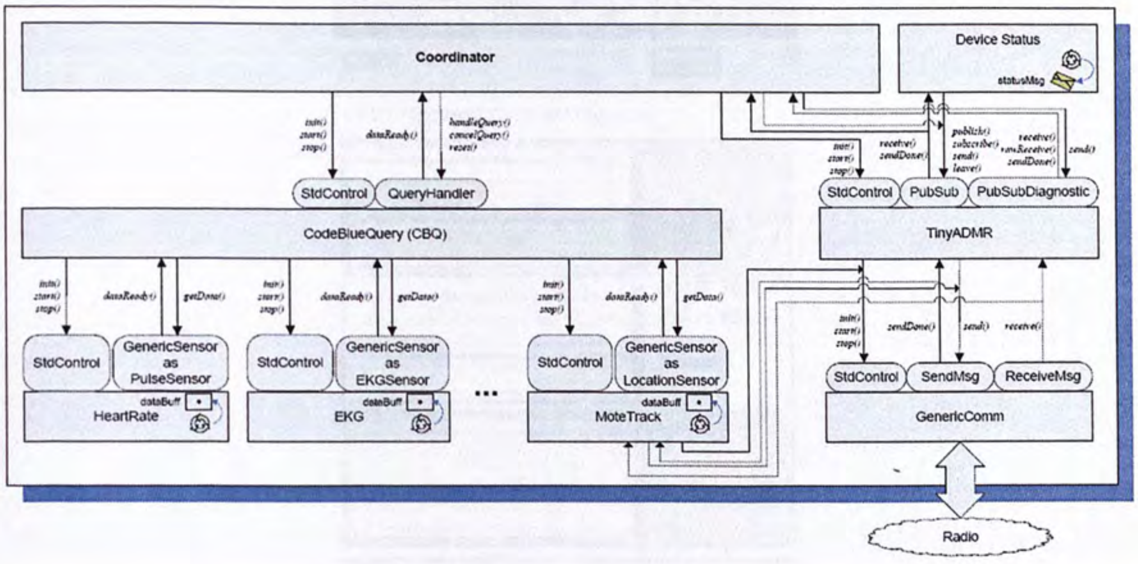
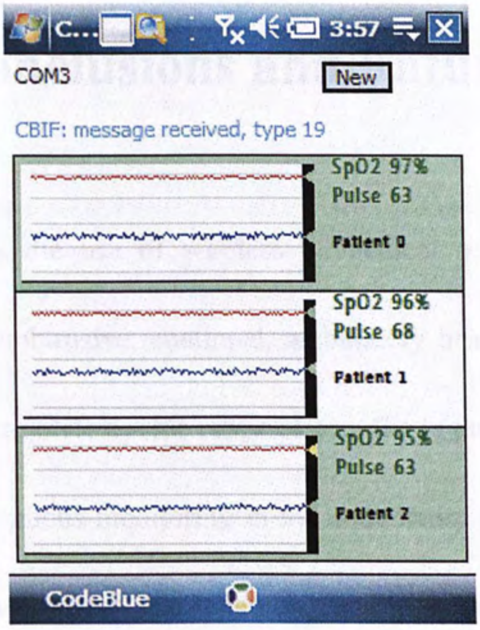


Figure 4-5: The CodeBlue software architecture.

CodeBlue is based on a publish/subscribe routing framework, allowing multiple sensor devices to relay data to all receivers that have registered an interest in that data. This communication model fits naturally with the needs of medical applications where a number of caregivers may be interested in sensor data from overlapping groups of patients. A discovery protocol is provided to allow end-user devices to determine which sensors are deployed in a CodeBlue network, while a query interface allows a receiving device to request data from specific sensors based on type or physical node address. The query interface also provides a filter facility, whereby a query can specify a simple predicate on sensor data that will transmit only when the data passes the filter. For example, a doctor might request data on a patient only when the vital signs fall outside of a normal range.



CBIF: message received, type 19

SpO2 97%
Pulse 63
Patient 0

SpO2 96%
Pulse 68
Patient 1

SpO2 95%
Pulse 63
Patient 2

Figure 4-6: PDA-based multiple-patient triage application.

Handheld computers carried by first responders can receive and visualize multiple patients' vital signs. Figure 4-6 shows our PDA-based triage application, which displays real-time data from multiple patients and can report alerts should a patient's vital signs exceed a predetermined range.

Chapter 5 Conclusions and Future Work

This thesis demonstrates the use of wireless biomedical sensor networks as a key infrastructure enabling unobtrusive, continual, ambulatory health monitoring. This new technology has potential to offer a wide range of benefits to patients, medical personnel, and society through continuous monitoring in the ambulatory setting, early detection of abnormal conditions, supervised rehabilitation, and potential knowledge discovery through data mining of all gathered information.

In this work, we first proposed and implemented a WBSN node platform, called MediMesh sensor node, which serves as a research platform for study and evaluation of wireless biomedical sensor networks. The realized MediMesh sensor node is miniature and light weighted (a wearable device), low-power (a long term monitoring device) and flexible (a research platform). Apart from the hardware of MediMesh sensor node, we also described the software we have implemented based on TinyOS, which is a lightweight open source operating system designed uniquely for wireless sensor networks. Then in chapter 3, we presented several medical sensors custom built for our MediMesh sensor node, including a pulse oximeter, a EKG sensor, a sensor measuring galvanic skin response and a motion sensor. We considerately designed the sensor circuit and selected the electronic components to fit the need to be miniature and low-power. The outcome turned out to be satisfying. In chapter 4, we have described a general WWBAN architecture, important implementation issues, and our prototype WWBAN based on MediMesh sensor node platforms and custom-designed EKG, pulse oximeter and motion sensors. We have addressed several key technical issues such as sensor node hardware architecture and software architecture. We implemented the programs both for the workstation PC and handheld PC. They can acquire physiological data from the patient, display the data on the screen and store the data for later processing. A medical database is built on the workstation PC, which store the patients' identification data, physiological data and also diagnosis. The program can also signal an alert in case the physiological signals exceed normal level. And in the last part of this chapter, we present a triage application based on CodeBlue by Harvard, which is an application of wireless biomedical sensor networks in ambulatory settings.

Our evaluation of the prototype points to a number ofcritical areas for future work. The most serious is the lack of reliable communication, although our results show that this problem can be mitigated somewhat through redundant transmissions. Further efforts are necessary to improve QoS of wireless communication, reliability of sensor nodes, security, and standardization of interfaces and interoperability. In addition, further studies of different medical conditions in clinical and ambulatory settings are necessary to determine specific limitations and possible new applications of this technology. We do not believe that reliable routing is required for all medical data; rather, the system should allow each query to specify its reliability needs in terms of acceptable loss, data rate, or jitter.

Another area worth exploring is the impact of bandwidth limitations and effective techniques for sharing bandwidth across patient sensors. For example, each CodeBlue query could specify a data priority that would allow certain messages (say, an alert from a critical patient) to have higher priority than others in the presence of radio congestion.

In conclusion, this paper has presented an initial exploration into the challenges of hardware and software design for medical sensor networks. We believe that low-power wireless sensors have the potential for tremendous impact in many medical applications.

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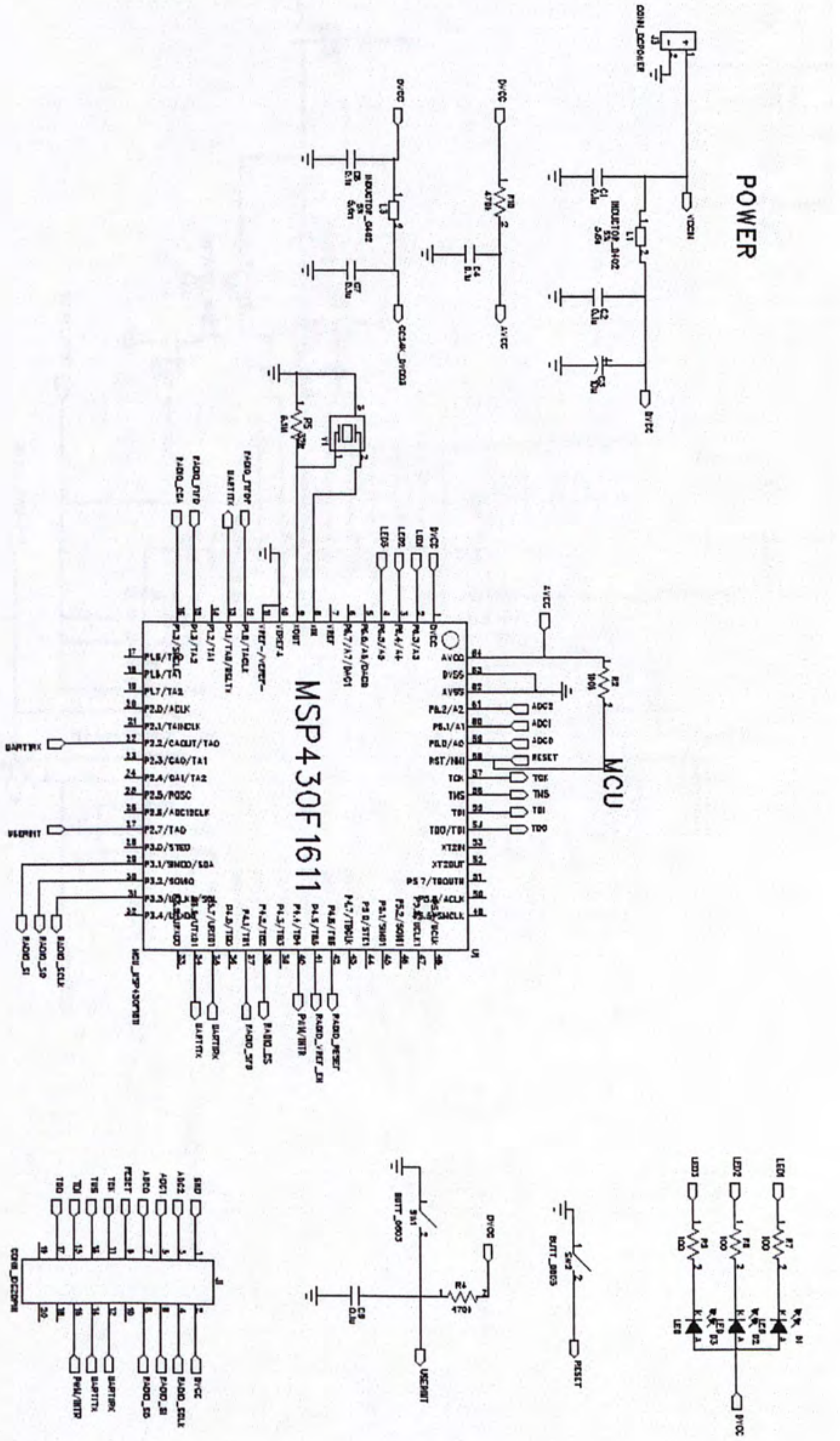
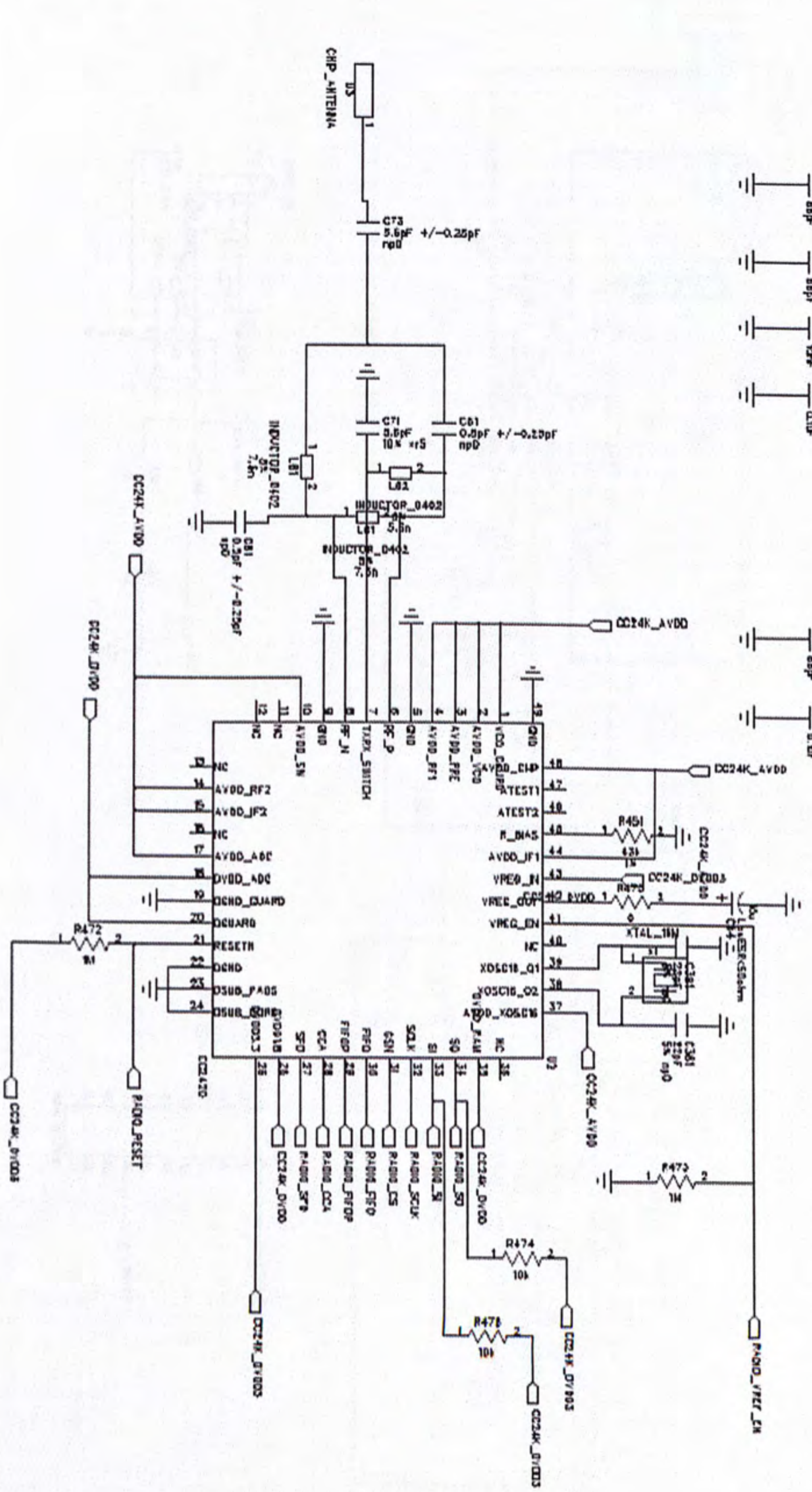
Appendix

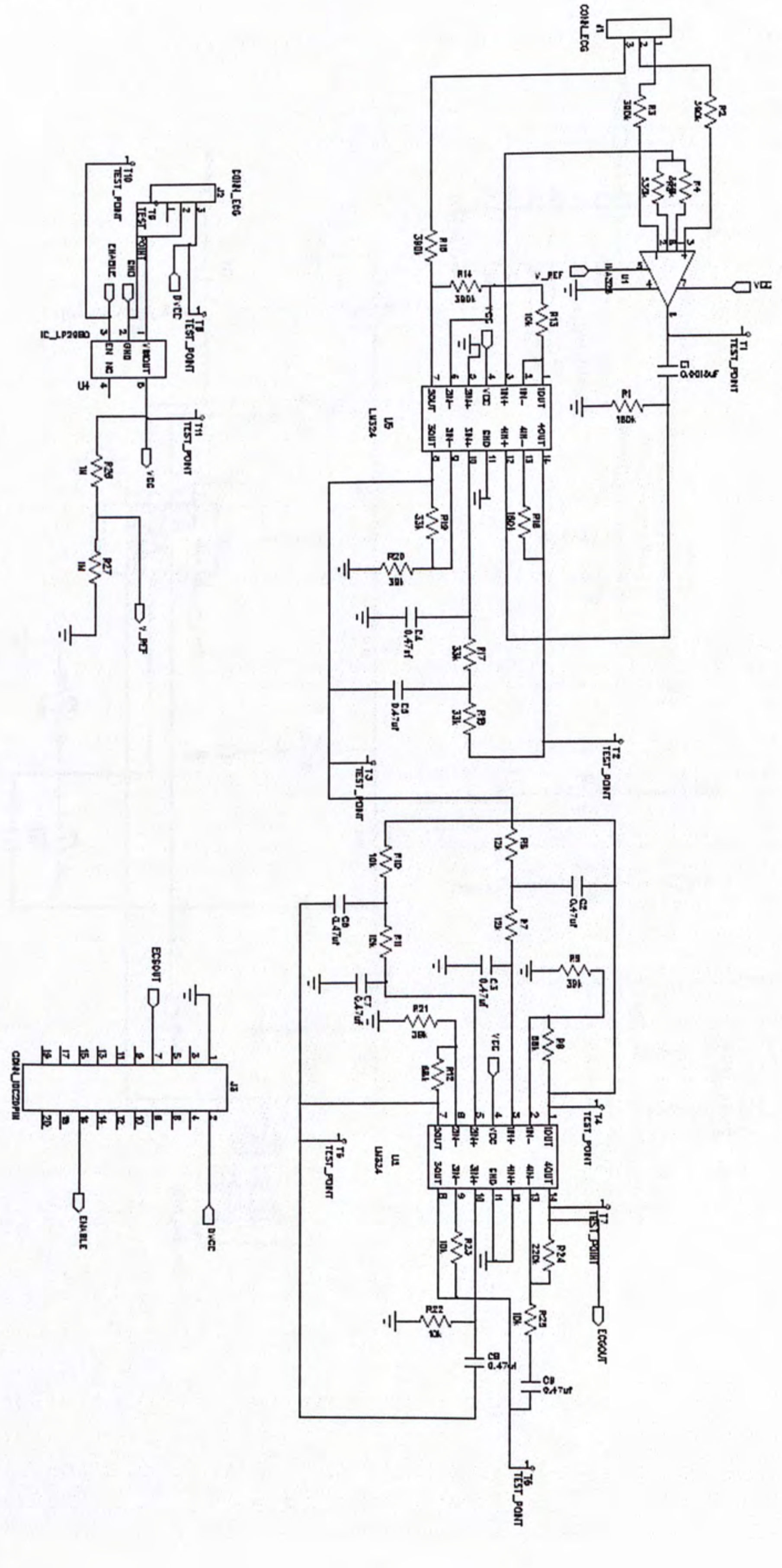
A. Microcontroller circuits



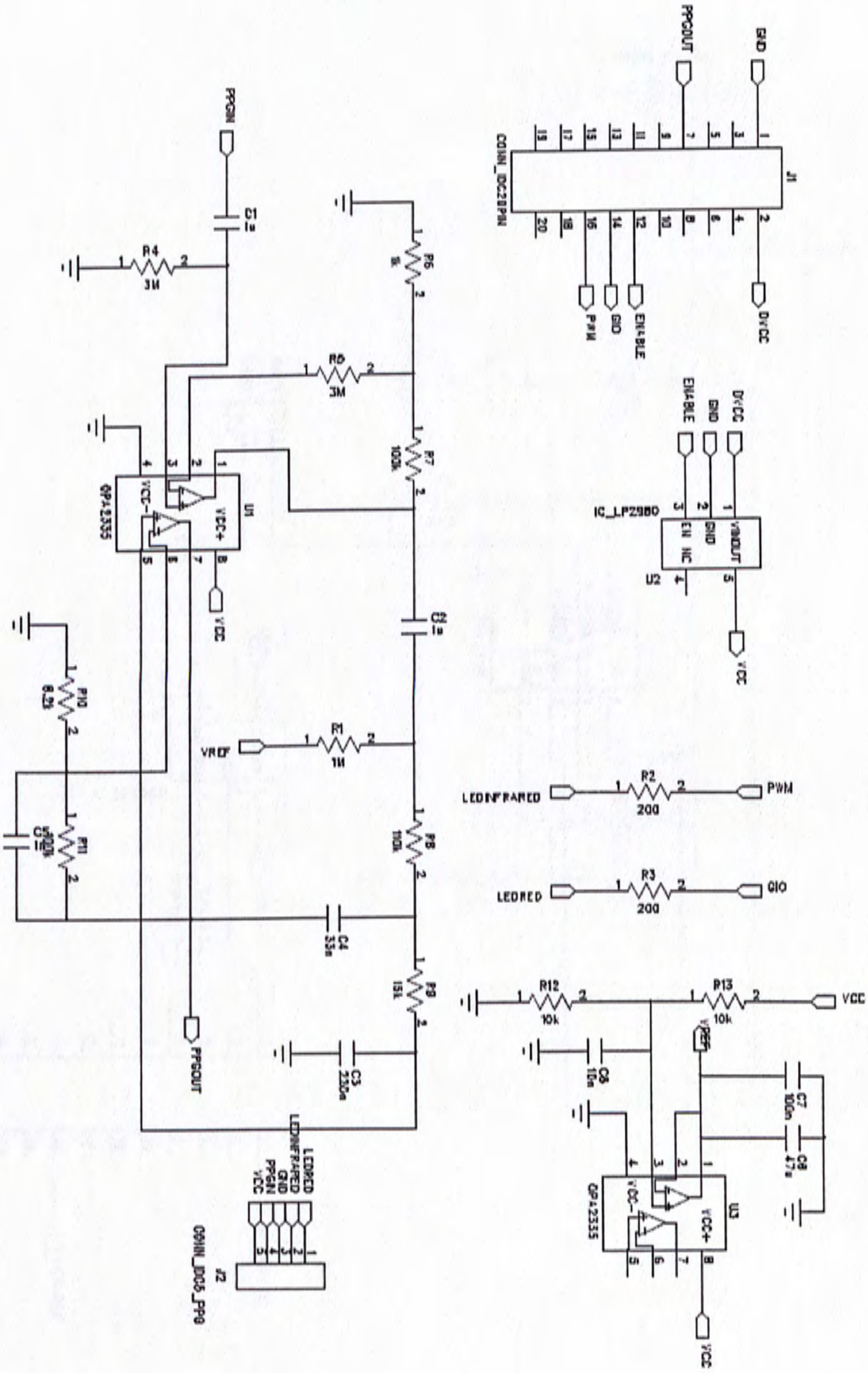
B. Radio circuit



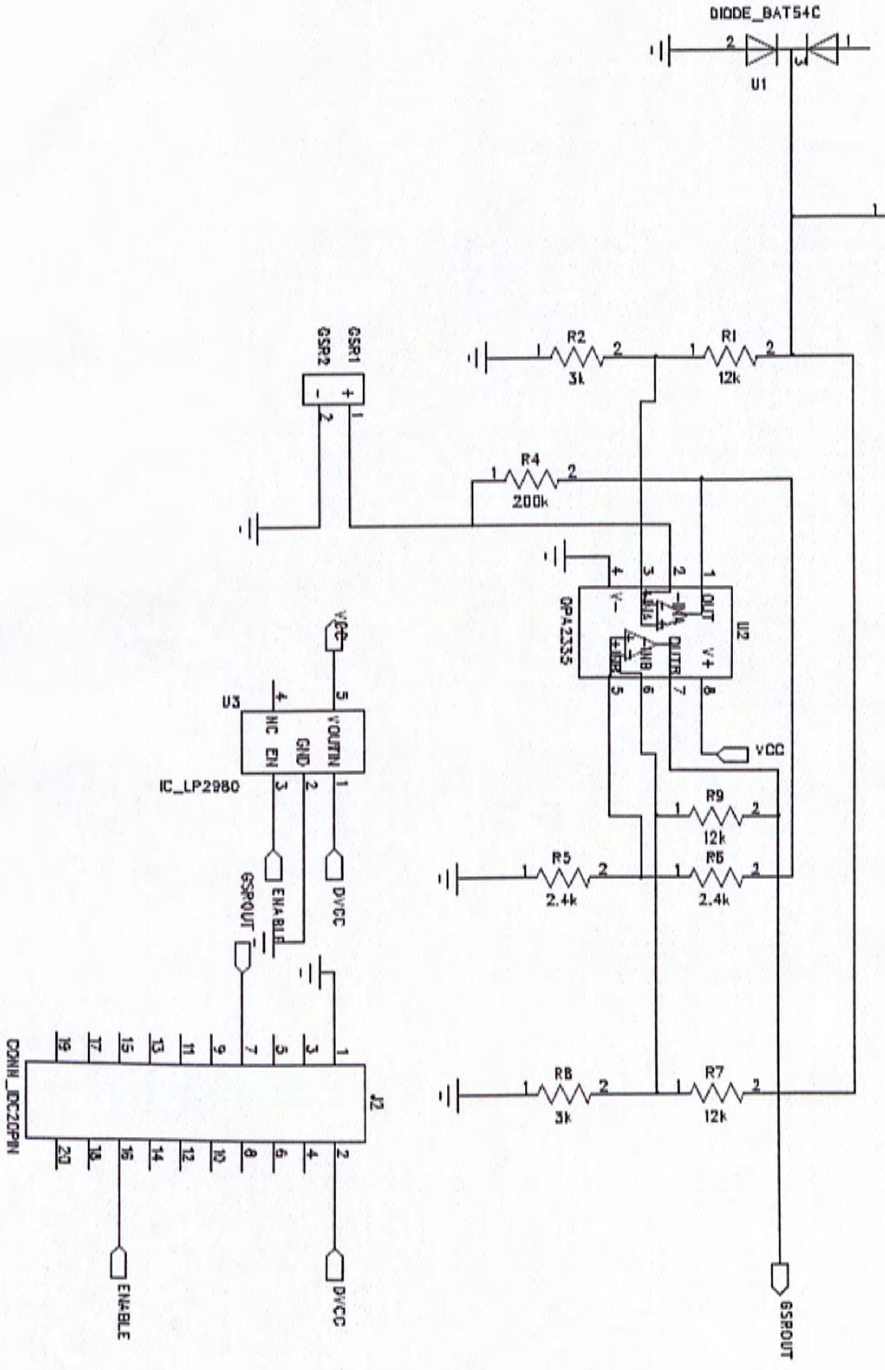
C. ECG circuits



D. PPG circuits



E. GSR circuits



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