[UCI]I804:24011-200000241851

2011 년　8 월
박사학위 논문

On-Node Processing and Priority Aware Medium Access for Energy-Efficient and Reliable ECG Monitoring over Body Area Networks

조선대학교 대학원

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2011 년 4 월

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요 약

BAN 기반 심전도 모니터링의 에너지 효율과 신뢰성 향상을 위한 온노드 프로세싱 및 우선순위 MAC

증 민

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무선 통신과 센서 기술의 발전으로 널리 사용되고 있는 무선 센서 네트워크(WSN)에서 인체의 생리신호를 관측하는 것은 새롭게 대두되고 있는 응용 분야이다. 그러나 전송데이터의 신뢰성 확보를 심각하게 고려하지 않는 WSN 특성상 잘 설계된 WSN일지라도이러한 인체통신분야에 이상적으로 적합하지 않다. 인체통신망(BAN)에서는 장시간 모니터링을 위한 센서노드의 전력 소모량은 최소한으로 감소시켜야 할 뿐만 아니라 생명과 관련된 정보는 네트워크 상에서 신뢰성 있는 전송이 요구된다. 따라서 전력소비 절감과 신뢰성 있는 전송 링크를 가지고 헬스케어 분야의 요구에 따른 인체통신망(BAN) 개발이 필요하게 되었다. BAN 기반의 연속

적인 모니터링 시스템은 만성질환의 건강상태 관리에 매우 큰 유용성을 가지고 있다. 이 시스템은 환자의 활동에 제한을 주지 않고 모든 환경에서 생리신호를 모니터링 할 수 있게 한다.

배터리 전원을 사용하는 센서노드는 매우 제한된 에너지 사용량을 가지므로, 에너지 효율성은 BAN의 헬스케어 응용에서 가장 중요한 과제 중의 하나이다. 센서노드는 바이오 신호를 지속적으로 감지하고 전달함으로 에너지 소모가 심하여 오랜 시간 모니터링 하기 어렵다. 그러나 센서노드의 수명을 연장하도록 효율적인 방법으로 에너지를 사용할 수 있다. 지금까지 센서노드의 에너지를 절약하기 위한 세가지 주요한 방법들로 저전력 하드웨어 디자인, 계산량을 줄인 소프트웨어 설계, 스마트 운영 메커니즘이 제시되었다. 이에 대한 관심과 노력들이 저전력 트랜시버와 프로세서와 같은 하드웨어 뿐만 아니라, 계산량을 줄이는 MAC 프로토콜이나 라우팅 프로토콜 같은 소프트웨어를 설계하도록 하였다. 그러나 몇몇 설계만이 현존하는 ECG 분석 알고리즘을 직접 적용하였거나, 간단한 측정 시간과 ECG 신호의 증폭으로 시스템 운영 메커니즘의 관점에서 센서노드의 전력 소비를 절감 하였다.

본 논문에서는 센서노드에 지능을 부가하여 스마트 운영함으로써 에너지를 절약하는 방법을 제시하였다. 즉, 센서노드에서 수집한 신호를 지속적으로 전송하지 않고, 수집한 신호의 정상 또는 비정상 여부를 판별하고 비정상 생체신호의 발생여부를 알리는 신호만을 전송하는, 계산량이 간소화된 on-node processing을 제안하였다. 센서노드의 전력 소비량을 분석하였으며, ECG 모니터링 시스템 기반 지능형 센서노드의 프레임워크를 구성하였다. 센서노드에서 수집한 신호를 로컬 진단을 통하여 분류할 때, 높은 정확도 및 에너지 효율을 달성하면서도 계산량이 간소화된 ECG 분석 알고리즘을 제안하였다. 제안된 심전도 분석 알고리즘은, 측정된 ECG

사이클과 정상적인 ECG 사이클의 사이에서 유클리드 거리를 계산하고, 정상적인 ECG 사이클과 의사들의 보다 심도있는 진단이 필요한 비정상적인 ECG 사이클을 판별한다. 이와 더불어, 본 논문에서는, 수집된 의사진단용 ECG 사이클의 전송 신뢰도를 높이기 위하여 우선순위를 가진 MAC 프로토콜을 제안하였다. 우선순위를 가진 MAC 프로토콜은 다음 두 가지 특징이 있다. i) 긴급하지 않은 패킷의 백오프 타임을 늘려 패킷의 우선순위를 결정한다. ii) 채널에서는 긴급 패킷을 위해, 다른 모든 긴급하지 않은 패킷 전송은 중단되고 지워진다.

본 논문에서는 시뮬레이션 및 구현을 통하여 제안된 로컬 ECG 분석 알고리즘과 우선순위 기반 MAC 프로토콜의 효율성을 보였다. 로컬 ECG 분석 알고리즘은 전력 소비와 진단의 정확성이라는 두 가지 측면에서 평가된다. 우선순위가 지정된 MAC 프로토콜은 평균 패킷 지연, 재전송율, 처리량이라는 세 가지 측면의 실험결과를 통하여 ECG 모니터링 시스템 기반의 지능형 센서노드의 에너지 효율 및 신뢰성 향상을 보였다.

I. Introduction

A. Overview

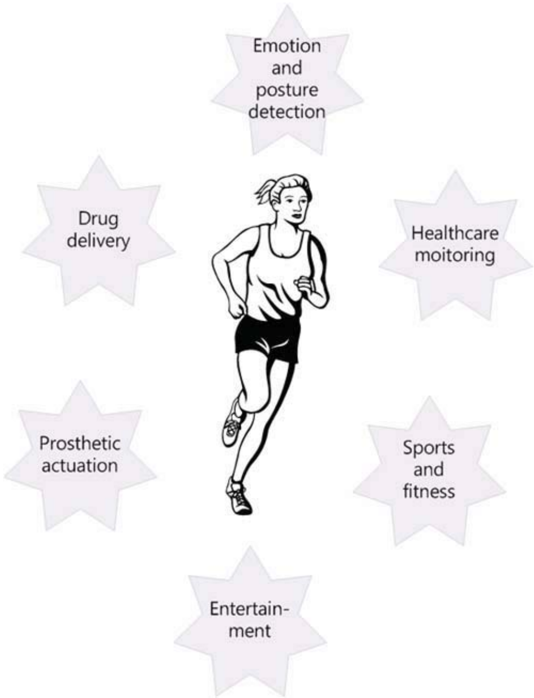
Aging population and sedentary lifestyle are leading to the prevalence of chronic diseases such as heart diseases, high blood pressure (hypertension), stroke, diabetes, etc [1]. According to the World Health Organization (WHO), cardiovascular disease causes 30 percent of all deaths in the world. Diabetes currently affects 180 million people worldwide and is expected to affect around 360 million by 2030 [2]. In addition, the worldwide population over age 65 is expected to more than double from 357 million in 1990 to 761 million in 2025 [3]. All these statistics suggest the proactive managing of wellness rather than illness, and focusing on prevention and early detection of diseases.

Continuous healthcare monitoring is a useful solution in helping the transition to more proactive and effective healthcare. For heart diseases, continuous monitoring of the heartbeat information ensures control of the heart rate and prevention of related mortality. For high blood pressure, once the treatment of hypertension is commenced, it is titrated to the required effect by monitoring the patient's blood pressure over a period of weeks or months. Once patients have been diagnosed with hypertension, they require regular blood pressure monitoring to ensure adequacy of therapy. Therefore, people who are old or suffering from chronic diseases need continuous monitoring of their physiological parameters. It allows an individual to closely monitor changes in her or his vital signs and provide feedback to help maintain an optimal health status. This burgeoning healthcare needs are exerting enormous strain on the healthcare delivery system. Moreover, the shortage of skilled staff, the overload, and the tightening of healthcare budgets have aggravated the impending healthcare crisis. These social, economic trends highlight the need to exploit technological breakthroughs to bring efficient and affordable healthcare solutions to people who have chronic diseases.

At the same time, with the development of wireless communication, sensor design, and energy storage technologies, wireless sensor networks (WSNs) have become a reality. The applications emerging for WSNs can be categorized into three types as follows: those used for monitoring environments such as indoor, outdoor, and urban or countryside, monitoring objects such as machines and buildings, and monitoring the interaction of these objects with environments. It covers a wide range, from industrial automation to animal life habit monitoring, from bridge structure monitoring to microsurgery, and so on.

Advances in WSN technology have opened a new era for conquering healthcare challenges, while the WSN technology does not specifically tackle the challenges associated with healthcare applications. The human body consists of a complicated internal environment that responds to and interacts with its external surroundings, but is in a way “separate” and “self−contained”. In essence, the human body environment is not only on a small scale, but also requires a different type and frequency of monitoring, with appreciation of different challenges than those faced by WSNs. There has been considerable interest in the development and application of WSNs for human body monitoring. Researchers in computer, networking, and medical fields are working together in order to make the broad vision of WSN based healthcare system possible. Therefore, human body monitoring using a network of bio-sensors may be achieved by attaching these sensors to the body surface as well as implanting them into tissues. However, the well-designed WSNs are not ideally suited to monitor the human body and this has led to the development of a Body Area Network (BAN).

The BAN technology originated from healthcare applications, addressing the weaknesses of traditional patient data collection. BANs continuously capture quantitative data from a variety of sensors, such as Electrocardiograph (ECG) sensors, Electroencephalograph (EEG) sensors. By addressing challenges such as energy efficiency, communication reliability, BANs can enable long term telehealth applications and facilitate highly personalized and individualized healthcare. By real-time sensing, processing, and control, the BAN technology can augment and preserve body functions and human life. Besides patients, BANs can also protect those exposed to potentially life-threatening environments, such as soldiers and deep-sea explorers. In addition to long term monitoring, efforts are also devoted to improve deep brain stimulation, drug delivery, and prosthetic actuation. Moreover, BANs with other different devices can also excel in healthcare scenarios, serving the interests of multiple stakeholders [4]. Physiological and biokinetic sensing applications are increasing as athletes and fitness enthusiasts seek to improve human performance and gaming systems are endeavoring to integrate more sophisticated interfaces based on human movements. Fig. 1 illustrates some of the applications BAN technology is intended to support.



(Figure 1) BAN applications

The design challenges and research issues of BANs depend greatly on the specific application and deployment environment. They have to not only tackle the problems already existing in WSNs, but also fulfill the specific application requirement. In general, the following technical aspects should be emphasized in healthcare application BANs.

- Sensor and platform miniaturization. Healthcare applications require very small, lightweight, and wearable sensors, especially for implant applications.
- Energy efficiency. Each sensor platform has limited power capacity, so efficient usage of the energy is very critical to prolong the lifetime of the

BAN. It includes low power hardware and software, and smart system working mechanism design.

- Reliable and secure communication. Data delivered in the BAN is related with people's physical conditions. Therefore, transmission of this information should be reliable to ensure that the patient can receive timely treatment, and secure to protect the patient's privacy.
- Power scavenging. So far batteries still remain the main power source of the sensor platform. Replacement or recharging introduces the cost and convenience penalty. As for implant applications, this is not even possible. As an alternative, sources which scavenge energy from the environment are therefore highly desirable.

B. Motivation

Many healthcare application aspects of the BAN technology have been researched, among which the continuous monitoring of people who are suffering from cardiovascular related illnesses is the most remarkable. Abnormalities of heart rhythm are commonly encountered in clinical practice, occurring in as many as 4% of the population over the age of 60, increasing with age to almost 9% in octogenarians [5]. Early symptoms of heart diseases include fatigue and palpitations, and often lead to the patient seeking medical advice. An ECG signal is useful for a doctor to evaluate a patient's heart condition relating to whether a heart attack or an irregular heartbeat has occurred. Thus, continuous ECG monitoring performed to detect possible symptoms is very critical to ensure the control of the heart status, which results in prevention of much of the associated morbidity and mortality. Therefore, ECG monitoring is one of the most interesting and popular application for BAN technology.

In BAN based Wireless ECG monitoring systems, the long cables between nodes are eliminated so that the patient is comfortably able to move around. The doctors and nurses can obtain the patients' ECG signals in a trouble-free approach. For patients in rural and regional areas, the ECG information can also be sent via internet to a doctor for examination.

Even though many efforts have been devoted to developing efficient BAN based monitoring systems, they also present a set of challenges. Energy efficiency and transmission reliability issues, which are important aspects for WSN technology, are of particular concern, given the continuous monitoring application, and significantly affect the efficiency of the overall monitoring system.

The lifetime of a WSN is application specific. With continuous healthcare application, it is necessary to monitoring a patient's condition continuously because an event can occur at any time. Most of the continuous monitoring systems as well as ECG monitoring are aiming at long term supervision and control. So bio-signals have to be transmitted to the doctor all the time and the energy hungry radio transceiver has to be running continuously in order to perform real time diagnosis, which shortens the life time of sensor nodes and the whole monitoring system. In addition, thus far, battery remains the main source of energy for sensor nodes, which has limited energy capacity and inconvenient or impossible to be recharged in time. Therefore, the sensor node is required to be extremely energy efficient so that it can sustain as long as possible. Thus we believe that the energy efficiency issue is one of the most important challenges obstructing the widespread and efficient use of continuous ECG monitoring systems.

In addition, from WSNs to BANs, it has a higher requirement for transmission reliability. Reliable data communication is an important factor for the dependability and quality-of-service (QoS) in healthcare applications of BAN technology. This is very closely related to the performance of the continuous monitoring systems. In healthcare applications, a great emphasis is placed on data availability. Doctors have to diagnose diseases based on the data transmitted from sensor nodes. So packet loss during the transmission may lead to loss of important information and the delay may lead to the missing of the best treatment timing. Therefore, transmission reliability is also a very important and challenging issue in continuous ECG monitoring system.

In this research, we investigate an energy efficient scheme for ECG monitoring system as well as other continuous physiological parameter monitoring. Moreover, we present a reliable transmission scheme to ensure the dependability of the healthcare monitoring system.

C. Contributions

In this thesis, we address the energy efficiency and reliability issues in BANs for continuous ECG monitoring system. Our major contributions are as follows:

- We thoroughly analyze the power consumption in continuous ECG monitoring system and setup the framework of intelligent sensor node based ECG monitoring system.
- We propose a light weight ECG analysis algorithm for saving energy of the sensor node, which achieves sufficiently high accuracy and energy efficiency.
- We propose a reliable prioritized MAC protocol (pMAC) to ensure the delivery of critical information to the doctor.
- We provide extensive experimental simulation and implementation results for validating the efficiency of the proposed schemes.

D. Thesis Outline

The rest of this thesis is organized as follows. In Chapter II, we describe basic background of continuous monitoring systems and articulate the related works in energy efficiency and reliability issues in BANs for healthcare applications. In Chapter III, we describe the intelligent sensor node based ECG monitoring system for reducing power consumption. We present a specific power consumption analysis of the sensor node and propose a light weight ECG analysis algorithm for the local sensor node to achieve high energy efficiency. In this chapter, we also extend to include a prioritized MAC protocol to improve the transmission reliability of intelligent sensor node based ECG monitoring system. In Chapter IV, we present evaluation and analysis of the proposed approaches. We analyze the local ECG analysis algorithm in power consumption and diagnosis accuracy. In this chapter, we also evaluate the prioritized MAC protocol through the averaged packet delay, transmission probability, and throughput. Finally, Chapter V concludes the thesis with future directions.

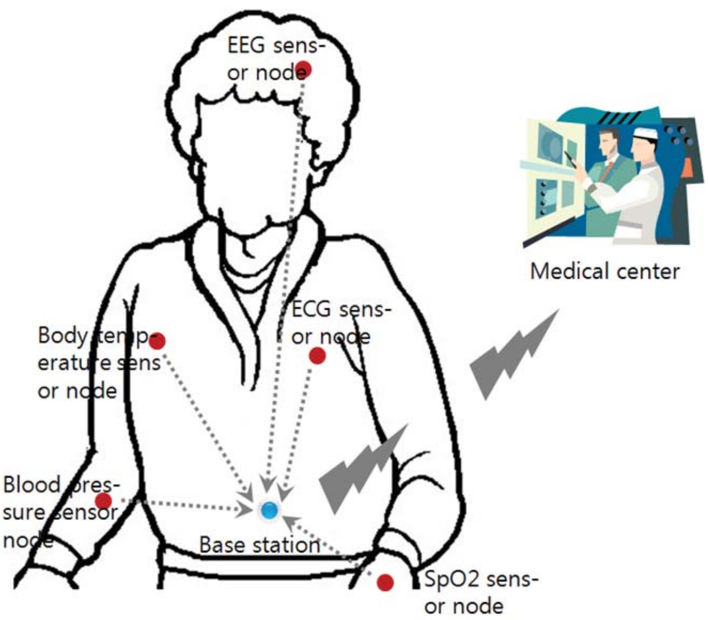
II. Background and Related Work

A. Traditional BAN based Continuous Monitoring System

Basically, the body area network is a radio frequency based wireless networking technology that interconnects tiny nodes with sensor or actuators in/on/around a human body. Using wearable medical sensors based body area networks, real time medical data about patients' physiological status can be collected conveniently. Comparing to wired continuous monitoring systems, BAN based wireless continuous healthcare monitoring systems offer two main advantages over conventional healthcare monitoring approaches [6]. First, it is cableless to the human body, thus monitoring distance can be greatly increased. Therefore, patients are not confined in the hospital any more. Second, without the inconvenience of the wire, more sensors can be placed on the patient's body, so that more information about the patient's physical condition and environment context can be obtained.

1. System Architecture

Traditionally, a BAN based monitoring system is configured like this (see Fig. 2). The patient is with a number of biosensors, which are capable of measuring significant physiological parameters. For example, an ECG sensor can be used for monitoring heart activity and an EEG sensor can be used for monitoring brain electrical activity. In addition to a patient's vital signs, a person is also physiologically very sensitive to context or environment changes. So motion sensors, temperature sensors, and other sensors reflecting environment conditions are needed to be equipped. All the sensors need to be miniaturized, wearable and light weight, so that they can be equipped without disturbing the patients' activities.



(Figure 2) BAN architecture

These sensors are attached to the patient's body and also connected to the sensor node which is an embedded system consisting of a processor, a transceiver, a memory unit, transducers and a battery pack. The sensor node with biosensors can sample, process, and transmit the vital signal to a base station without constraining the activities of the wearer. Since the monitoring is real time and the patient may be attacked any time, all the components of the sensor node have to work all the time so that the critical sign of possible attack can be detected and delivered to the doctor as soon as possible.

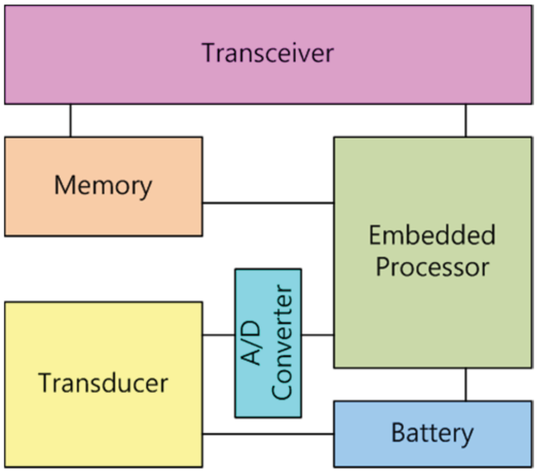
The base station is used to collect physiological signal and display or send this information to the doctor. Through the base station, the sensor node can contact the outside world by other kinds of networks and report the events inside the BAN. As the sensor nodes continuously sense and transmit physiological signals to the base station, doctors and nurses can capture any abnormality of patients, whenever and wherever patients are.

The ECG signal is useful for a doctor to evaluate a patient's heart condition relating to whether a heart attack has occurred, what parts of the heart are damaged, whether the heart is not receiving enough blood or oxygen, and irregular heartbeats. It is extremely valuable, making it a conventional mechanism used in hospitals by doctors and nurses. By eliminating the long cables between nodes, the patient is comfortably able to move around without the hassle of wires, while also being able to place the electrodes on themselves without being impeded by leads. Similarly it provides the doctor or nurse with a trouble-free approach to access the patient's ECG signal. In addition, software could allow ECG signals to be saved and sent possibly by email to other parts of the world. For people who live in rural and regional areas, this is especially useful in keeping contact with doctors for examination. Therefore, it is very significant to develop a wireless ECG monitoring system to provide more user-friendly healthcare services.

2. Sensor Node

For every base station, a network of sensor nodes captures various physiological signals of healthcare interest. The sensor node has an important role in the whole BAN system. Each node is capable of sensing, sampling, processing physiological signals, and communicating with each other. The sensor nodes must satisfy requirements for minimal weight, miniature form, and low power consumption to permit prolonged ubiquitous monitoring, seamless integration into a BAN, standards based interface protocols, and patient−specific calibration, tuning, and customization. The sensor nodes continuously collect, process, and transmit raw information to the base station. The type and nature of the healthcare application determine the frequency of relevant events. With further development of the technology, the sensor node can be implemented as tiny patches or incorporated into the user's clothes. The working performance of the sensor node determines the efficiency of the whole system. Therefore, it is necessary to improve the working efficiency of the sensor node to the greatest extent.

Usually, a sensor node consists of four sub−systems [7] (see Fig. 3). The computing sub−system consists of two sub−modules, namely, the embedded processor and the storage unit. It is used to control the components of the sensor node and perform any required computation. The communication sub−system is used to support the sensor nodes to communicate with each other and with base station. The sensing sub−system translates physical phenomena to electrical signals and it's the link of the sensor nodes to the outside world. The output of the sensors is analog signals, so an analog to digital converter (ADC) needs to be included in order to allow the processor to read the data. The power sub-system usually refers to an attached battery which supplies power to all other sub-systems.



(Figure 3) Sensor node structure

B. Related Work

1. BAN based Continuous Monitoring Systems

Many efforts have been devoted to demonstrating the clinical efficacy of various BAN systems in healthcare applications. The most famous one is the "CodeBlue" project at Harvard University. This project is intended for deployment in a hospital. They developed a medical sensor network that incorporates wireless pulse oximeter sensors and ECG sensors to monitor and record vital signs and cardiac information [8, 9]. By using the Mica2 motes, developed by UC Berkeley and manufactured by Crossbow Technology, Inc. [10], attached with sensors, the developed system allows the wireless transmission of continuous cardiac rhythms and other bio-signals. These data could ultimately be received by PDAs, desktop PCs or other wireless enabled devices in a multitude of healthcare scenarios. This research is twofold, comprising both hardware, interfacing an ECG sensor board with the Mica2 platform, and software, reliably capturing ECG data and transmitting it wirelessly to a nearby receiver.

Mobile cardiac outpatient telemetry system (MCOT), developed by a company called CardioNet, allows patients to be monitored for an extended period and is effective in the diagnosis of clinically significant, symptomatic, and asymptomatic cardiac arrhythmias [11, 12]. The CardioNet Monitoring Center provides physicians with the succinct, integrated information that they need for diagnosis and therapy management. This system is proved to be very efficient through a 17-center prospective clinical trial.

The “UbiMon” project proposes a ubiquitous monitoring system with wearable and implantable sensors to provide continuous management of patients under their natural physiological states so that transient but life threatening abnormalities can be detected and predicted [13]. In addition to the physiological parameters, the context awareness aspect is also included in this system to enhance the capturing of any clinical relevant episode. The use of this system for post-surgical care, especially in conjunction with minimal access surgery, is very significant in improving the patients' lives after surgeries.

The mobile healthcare project “MobiHealth” is developed focusing on home care, trauma care and ambulatory monitoring. It allows patients to be fully mobile whilst undergoing health monitoring by deploying a wireless BAN with the integration of sensors and actuators. This system can measure and transmit vital constants, ranging from blood pressure and pulse rate, to oxygen saturation and ECG information, to health service providers and brokers, improving the quality of life of patients and the elderly people [14, 15, 16]. In addition, images and video can be captured and transmitted to the health center from the accident site, so that doctors can make more accurate diagnosis.

More recently, a research group in Finland developed an ECG measurement, analysis, and transmission system which uses a mobile phone as a base station [17]. The system is based on a small sized mobile ECG recording device which sends measurement data wirelessly to the mobile phone. The computing capabilities of the phone are used to make signal processing and analysis of the measured signals. In the mobile phone, the received ECG data is analyzed and if abnormalities are found, part of the measurement data is sent to a server for further diagnosis by medical personnel.

In [18], a smart shirt with wireless sensor network compatibility is designed and fabricated for continuous monitoring of physiological ECG signal and physical activity signal from an accelerometer simultaneously. It consists of sensors for continuous monitoring the health data and conductive fabrics to get the body signal as electrodes. This design is proved to be applicable to improve the accuracy of the patient diagnosis by the continuous monitoring with non-invasive, comfortable and convenient shirt to wear.

In [19], a telecardiology system using ZigBee [20] is designed and implemented. This system is capable of receiving a serial stream of data and extracting relevant packets from the measurements of the patient's vital signs. It provides doctors with the ability to monitor, and diagnose their patients remotely over the Internet. This research group proves that establishing such a technology can achieve reduction in effort and cost, with increased efficiency, and ease of use, which is very important in developing countries.

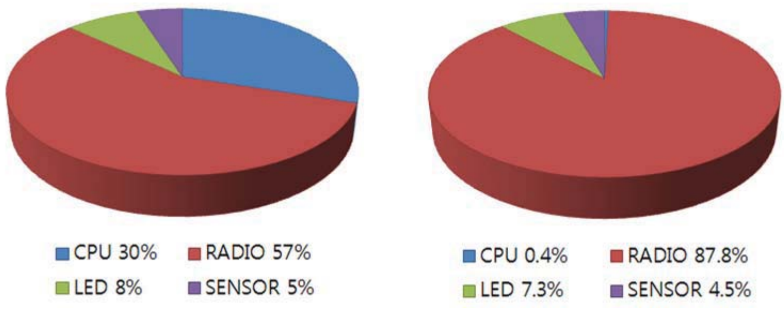
All these strategies share a common aim in providing unobtrusive, pervasive human monitoring irrespective of geographical location. An excellent survey of BANs for healthcare monitoring especially for ECG signal is presented in [21]. All these projects and research efforts have proved that the adoption of BANs for healthcare applications offers accurate, continuous, and most importantly, non-invasive monitoring of physiological, and environmental parameters. However, they also bring out some challenges of efficiently applying the BAN technology to healthcare monitoring applications as mentioned in Chapter I. Energy efficiency of the sensor node and reliability of the transmission link are the most prominent and need more efforts.

2. Power Consumption Issues and Existing Solutions

One of the key considerations for BANs is power consumption. This is because power consumption determines not only the size of the battery required but also the lifetime of the sensor node. Therefore, researchers are seeking every way to keep the sensor node working with very low power consumption.

Typically, a sensor node has four work modes: listen mode, process mode, transmit mode, and sleep mode. The power consumed in each mode is different. Based on our earlier research [22], in traditional BAN based continuous ECG monitoring system, power consumption percentage of each component for the sensor node is shown in Fig. 4.

This energy consumption information is obtained using PowerTOSSIM simulator, running the continuous transmitting ECG monitoring program, which is specifically described in Part IV. From this figure, we can see that about 57% of the total power consumption of sensor nodes is attributed to the transceiver component for the Mica2 mote. This is the direct result of continuously turning on the power−hungry radio transceiver component. The sensor node has to work in the transmit mode all the time to transmit ECG data to the base station so that doctors can perform real−time diagnosis. The second biggest energy consumer is CPU component with around 30% of the total power consumption. In the continuous transmission scheme, power consumption of CPU component only includes hardware power state transitions when collecting and transmitting ECG data and there are no extra CPU cycles used for ECG analysis computation. For the TelosB [23] mote, the radio consumes more power and the processor consumes less power comparing to the Mica2 mote. This is because of the usage of different hardware component. The processor used in TelosB is more energy efficient and the radio component is kind of more power consuming.



(a) Mica2 mote (b) TelosB mote

(Figure 4) Energy consumption distribution of the sensor node

For saving the power consumption of sensor nodes, researchers are seeking every method to achieve high energy efficiency including low power hardware design, lightweight software design, and smart working mechanism. The power issue in body area networks is researched from nearly all aspects.

a. Hardware Design

A sensor node's lifetime heavily depends on the attached battery and the sensor node may use up this limited energy during sensing, processing and communication process, which can lead to the possible missing of critical information in the healthcare applications. So many hardware designs related with transceivers, processors, and platforms have been proposed to save power in BAN based continuous monitoring systems.

The transceiver component is the most power−consuming component of the sensor node. It consumes large part of the total power consumption, which has been verified in our former work as mentioned above. Therefore, reducing the active power consumption of the transceiver can directly reduce the total power consumption as the transmission time is not changed. Several suitable license−free frequency bands are available to position the radio channel, such as 433 MHz European and 2.4 GHz worldwide Industry−Science−Medical (ISM) band. Based on different frequency bands, a lot of literatures have been presented on the low power solutions to the transceivers of the sensor node. In [24], a low power, low cost, high integrated transmitter working at the 2.4GHz ISM band is presented. More aggressively, a 1V RF transceiver for BAN applications is presented in [25]. More related low power transceiver designs are available in [26−30].

The energy efficiency of the embedded processor is also researched and some low power processors have been proposed. These designs are usually application specific, especially for ECG signals. In [31], an optimal processor for ECG signal processing is successfully built consuming 8.4μW when running the reference ECG application. Other low power processors related with ECG signal processing are proposed in [32, 33]. A general purpose processor for wireless

BANs is developed in TANDEM project [34].

Other hardware researchers are aiming at saving the power consumption of the sensor node from all aspects of its components. They are designed carefully to achieve high energy efficiency and small size. ECO sensor node, developed at University of California, is an ultra-wearable, low power, and expandable wireless sensor node [35]. In transmission mode, Eco sensor node not only consumes less power, but also transmits data at a higher rate than other nodes. The Eco sensor node uses 1/13 as much energy as MICA2DOT [36] to receive the same amount of data. In [37], they propose a specially-designed BAN development platform for on-body physiological measurements and body-proximal wireless data communications. Other platforms such as WiMoCA node [38], BAN node v3 [39] are all promising sensor platforms for healthcare applications.

Moreover, a novel method of achieving low power usage is to use the body coupled communication [40-42]. Using the body as a transmission medium, the data is not broadcasted to everywhere but sent along the body. The reason why this technology could be less power demanding in theory is that changing an electric field consumes less power than generating electromagnetic waves. Body coupled techniques opens the door for innovative new ubiquitous computing applications as low power BANs. But currently it is not widely researched and still stuck in the development phase.

b. Protocol Design

Besides these new hardware designs, a number of protocols have also been proposed as the software solution to the energy efficiency issue. In this way, power consumption is saved by flexibly managing the medium access behavior of the transceiver component. As summarized in [43], the major sources of energy waste include collisions, overhearing, idle listening, and control packet overhead. First, when a transmitted packet is corrupted it has to be discarded, and the retransmissions increase energy consumption and latency. The second source overhearing means that a node picks up packets that are destined to other nodes. The third source idle listening occurs when a node listens to an idle channel to receive possible traffic. Finally, sending and receiving control packets consumes energy too, and less useful data packets can be transmitted.

A large set of MAC protocols have been proposed for reducing power consumption in sensor networks. The dominant mechanism of reducing power at the MAC layer is turning the radio off periodically and during the sleep periods all components of the sensor nodes are set to the low power mode. This kind of MAC protocols can be categorized into two groups: asynchronous and synchronized. In asynchronous protocols, such as B-MAC [44] and X-MAC [45], basically, B-MAC uses Clear Channel Assessment (CCA), packet backoffs, acknowledgements, and Low Power Listening (LPL) for low power communication. Sensor nodes run their duty cycles independently and transmission relies on preamble sampling. The synchronized protocols can be subdivided into TDMA (Time Division Multiple Access) based and CSMA (Carrier Sense Multiple Access) based. In TDMA based synchronized protocols, such as S-MAC [46] and T-MAC [47], all the sensor nodes are activated simultaneously in order to attempt communication. But in

CSMA based synchronized protocols, also called hybrid protocols, such as SCP-MAC [48] and Z-MAC [49], sensor nodes adopt both contention based and contention free mechanisms to access channel, combining the strengths of TDMA and CSMA.

Furthermore, a lot of literatures proposed for medical BANs with star topology using master/slave communication have been proposed. In [50], they propose a low power MAC protocol, while incorporates synchronized communication between master and slave nodes, contention based transmission, and sleeping as much as possible for the sensor node, to avoid major sources of power consumption. Another energy efficient implementation of MAC protocol introduces a secondary channel, which is used for channel listening only. The benefit of the secondary channel is analyzed and validated in [51].

Some literatures are trying to integrate the characteristics of the healthcare applications into the protocol design. In [52], an energy efficient and low latency MAC protocol is presented. This scheme saves power by exploiting feedback information from distributed sensors in the network and adjusting protocol parameters dynamically to achieve best energy conservation. Another novel TDMA MAC protocol called H-MAC is described in [53]. It improves BAN energy efficiency by exploiting heartbeat rhythm information to perform time synchronization, which saves the energy for extra time synchronization.

c. System Working Mechanism Design

There are a number of products that offer the possibility of continuous ECG monitoring for short periods of time. They can be categorized as two main kinds. The most common type is developed for continuous recording of the heart's rhythms for one or two days. The data is stored on a flash card and transferred to the doctor's computer for analysis at a later time [54]. The other type does not store the data to an attached flash card but transmit it over the radio channel to a base station for storing, processing and feature extraction [55-58]. However, these approaches are either resulting in delay of treatment in case of occurrence of deadly symptoms or wasting unnecessary energy by using the radio channel to transmit all the raw data to the base station while the processing capabilities of the sensor nodes go unused.

Despite so many concerns about energy efficiency in BAN systems from the hardware and software aspects, a few studies have been published in adjusting the real-time system operation mechanism field for saving power. Based on the processing capability of the sensor node, ECG diagnosis can be performed locally, so that transmission of raw data is not necessary all the time. In [59], by using the proposed local ECG analysis method diseases are diagnosed from ECG features. Based on the fact that the duration of ECG waves and intervals in a normal adult human heart are usually within some ranges, they extract the characteristics of the ECG signal, such as the heart rate and variation in the R-R interval and QRS width, and then, check if they are within the standard ranges. In such a way, there are no communications between sensor nodes when the sensor nodes don't detect any abnormality.

A research group in the Netherlands [60] is concerned with detecting arrhythmias, like brachycardia and tachycardia based on heart rate variations. They introduce a simpler algorithm for processing the ECG signal and extracting the heart rate directly on the sensor nodes with similar quality comparing to the traditional approaches. Moreover, they also suggest combining the local heart rate diagnosis scheme and the traditional continuous transmitting scheme. The heart rate can be calculated through the day while full logging of the ECG signal at higher frequencies can be done twice a day at random intervals or when a problem is detected. To provide a more accurate assessment of the patient's current health, the fusing movement information is provided as well.

In [61], a real-time ECG signal diagnosis algorithm is proposed based on the multiscale morphological derivative (MMD) transform. The designed MMD based singularity detector is an algorithm able to reliably identify the Q wave, R peak, S wave and the onsets and offsets of the P wave and T wave, which are fundamental blocks of any ECG signal. Based on the detected characteristic points, the duration and amplitude features of the ECG signal are evaluated to categorize the tested ECG signal. This research group is also furthering their study by using wavelet transform for ECG analysis [62, 63].

In [64], a more aggressive local ECG analysis algorithm aiming at compressed ECG signal is presented. They apply a novel system to analyze and classify compressed ECG signal by using a principal components analysis for feature extraction and clustering of normal and abnormal ECG signals.

ECG signal analysis is a common means of detecting heart problems in patients. So far, many algorithms and methods have been developed for high quality analysis of the ECG signals. However, due to limitations in the processing power and memory that sensor nodes have, directly porting algorithms that were constructed for more advance computers to sensor nodes is not suitable. Therefore, optimized algorithms should be developed to meet the need of the sensor node.

3. Transmission Reliability Issues and Existing Solutions

The MAC layer is responsible for coordinating channel accesses, by avoiding collisions and scheduling data transmissions, to maximize throughput efficiency at an acceptable packet delay and minimal energy consumption. We have discussed the energy efficiency issue in MAC protocol design, which is the hottest research area. Besides regular MAC layer challenges of WSNs like energy efficiency, there are challenging problems that are specific to the MAC layer of BANs for healthcare applications. The most prominent one is the quality of service requirement of emergency traffic. The information delivered in healthcare BANs is related with life and life threatening events may occur at any time, which causes emergency delivery of this critical message to doctors. This emergency data should be guaranteed to be delivered with a reasonable delay. In some cases, it is even more important than the energy issue because the final goal of the designed system is to benefit the patients and loss of the life threatening information is not acceptable.

So far few works have been proposed focusing on reliable transmission in BANs for healthcare and medical applications. In B-MAC, actually, the usage of

CCA and ACK are some potential strategies for improve the link reliability, so we choose to use B−MAC as a baseline of the performance evaluation.

In [65], they designed a MAC protocol for healthcare sensor networks. It incorporates preemptive−resume priority packet scheduling for the sensor node and prioritized channel contention between sensor nodes. The analytical performance evaluation shows that this scheme gives preference to emergency traffic which is crucial for healthcare applications.

In [66], an urgency−based MAC (U−MAC) protocol is proposed, in which sensor nodes reporting urgent health information are given higher priority while the non−urgent packet is given low priority. The U−MAC prioritizes packets by cutting off the number of packet retransmission of sensor nodes with non−urgent health information, so that the urgent packets are more probably to be sent. In essence, this design is to increase the transmission probability of urgent packets.

In another design proposed in [67], a new MAC model for BAN to fulfill the rigorous requirements under realistic medical settings such as high reliability, low packet latency is proposed. A novel cross−layer fuzzy−rule scheduling algorithm is designed to include system constraints, such as application specific elements and residual energy elements, into the working mechanism of the MAC protocol. It guarantees that all packet transmissions are served with their particular application−dependent quality of service requirements without endangering body sensor nodes' battery lifetime.

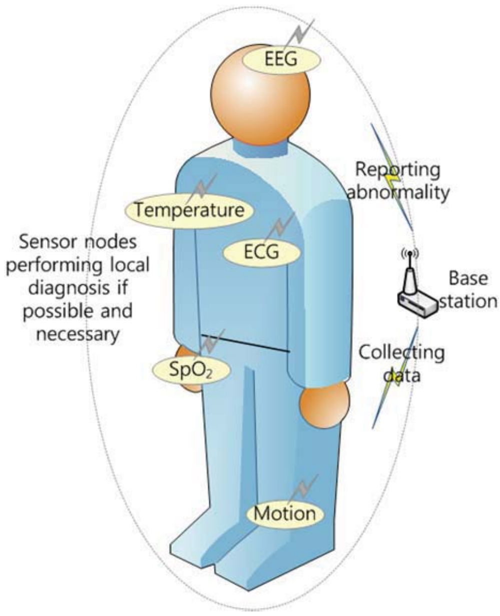
III. On−Node Processing and Priority Aware Medium Access for ECG Monitoring System

A. Intelligent Sensor Node based BAN Architecture

Body area network is a very promising method for providing convenient and low−cost supervision for patients that need continuous monitoring of vital signs. One sensor node can be used for continuously sampling a certain signal such as ECG, temperature, and more sensor nodes with different types of sensors can be networked together to provide a better assessment. This ongoing monitoring of patients means gathering and analyzing data continuously. It implies high energy consumption, hence a fast depletion of the batteries. The need for changing the battery frequently causes great inconvenience and almost impossible for implant sensor nodes. Therefore, prolonging the lifetime of the wireless devices is important. As we have discussed in Chapter II, the wireless transmission of information consumes the most energy and the processing and sleeping is less power demanding. In order to reduce the usage of the wireless communication link, either using efficient medium access schemes, or adopting on−node processing is viable option. This work introduces a novel intelligent sensor node based ECG monitoring scheme, which is an integrated research of ECG analysis and body area network technique.

1. System Overview

For cutting down the power consumption of the wireless link and reducing the total power consumption, the intelligent sensor nodes based system is very efficient. Fig. 5 shows the system architecture of intelligent sensor node based monitoring system.



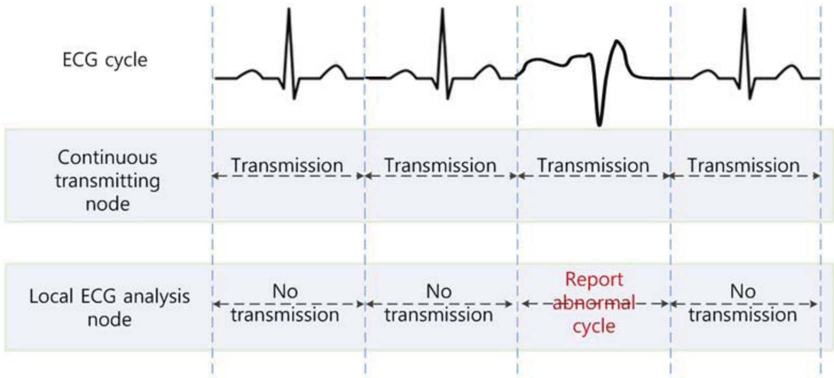
(Figure 5) Architecture of the intelligent sensor node based monitoring system

The base station is assumed to be rich in computational, communication, and storage resources. Its major task is to gather data from sensor nodes. The sensor nodes are assumed to be low-power mote platforms, such as Mica2 mote, TelosB mote etc. The task of sensor nodes is to sense, process, and transmit signals to the base station when appropriate, while archiving all data. The sensor node can do some local diagnosis, so that continuous transmission is not always necessary. Only when the node determines that the signal is abnormal, the transmission would be initiated. Currently, we are aiming at the ECG signal. But many other bio−signals of the human body also have a "rhythm"− a certain pattern. They can be modeled and classified as well, so the local diagnosis scheme can also be applied.

The major difference between the intelligent sensor node based monitoring system and the traditionally continuous transmitting monitoring system is the usage of the processing capability of the sensor node. By trading the computation for communication, local diagnosis substitutes for continuous transmitting. In such a situation, processing efficiency and accuracy of the sensor node determine the efficiency and value of the system.

2. System Operation

Assuming such a scenario, a base station is wirelessly connected to a sensor node through the 802.15.4 radio. The sensor node connected with ECG sensors that are attached to the human body continuously receives ECG signal of the patient. Then, the sensor node performs the local ECG diagnosis function as follows: at each sampling time t, the sensed ECG data is stored in the sensor node. After getting enough data, the local ECG analysis algorithm is run to locate one ECG cycle, and then, model the current cycle to extract the features of the ECG cycle. Finally the current cycle and the standard cycle are compared to determine whether or not it is necessary to give doctors and nurses an alarm signaling an abnormality of this patient's heart by launching a radio transmission (see Fig. 6).



(Figure 6) Operation mechanism of the intelligent sensor node based monitoring system

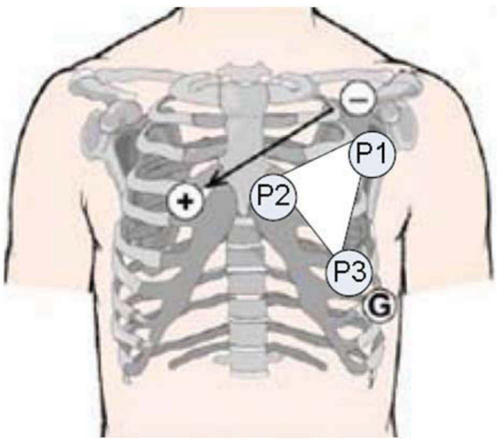
If the difference between the modeled cycle and the standard cycle exceeds a threshold, an alarm is sent to the base station. In contrast, if the difference is smaller than a threshold, then, the modeled cycle is assumed to be normal and the ECG data is only stored in the sensor node with no transmission. As soon as doctors and nurses receive the alarm through the base station, they can require the sensor node to transmit the recent ECG data stored in the sensor node and take urgent measures to help the patient.

As we know that the sensor node is resource-limited with the attached battery and could not afford computation intensive diagnosis method. Therefore, balancing the energy efficiency and the diagnosis accuracy becomes a critical point of the design. Existing algorithms in literatures are usually designed for computers and complex to be implemented on the sensor nodes. As analyzed in Chapter II, existing methods are either porting computer aided ECG analysis algorithms directly to sensor node, or extracting ECG cycle features only from the shape (such as height, duration). Optimized algorithms for ECG diagnosis need to be designed for the sensor node.

B. On−Node ECG Analysis Algorithms

1. ECG Signal Details

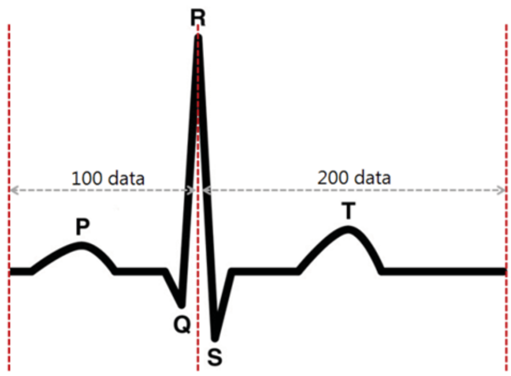
When the heart depolarizes and repolarizes, electrical current does not only spread within the heart but also to the adjacent tissue. A small portion of this current reaches the body surface. The ECG signal is the record of variation of bioelectric potential with respective to time as the human heart beats. It is measured by a number of non−invasive electrodes placed on the body skin. A lead is a view of the electrical activity of the heart from a particular angle across the body. ECG sensors are used to measure the time−varying magnitude of the electric fields emanating from the heart [68]. In this research, a 3−wire ECG sensor is used. The electrodes need to be placed in a triangle on the patient chest as show in Fig. 7.



(Figure 7) Placement of the electrodes for ECG signal recording

The ECG is represented by an analog signal which is continuous in time. The sensor reads the analog signal and the ADC transforms it into a digital signal. The ECG signal is formed of three basic waves: P wave, QRS complex, and T wave (see Fig. 8). P wave is caused by the depolarization of the atria, QRS complex is caused by the depolarization of the ventricles, and T wave is by the repolarization of the ventricles. For a normal heart, the main parameters inspected include the shape, the duration, and the relationship with each other. The changes in these parameters indicate a disease of the heart.

The sample size affects the segment selected for modeling and care must be taken to pick at least one completed cardiac cycle so that the signal can be accurately modeled and classified. In the current study, a complete ECG cycle consists of 300 data sensed by ECG sensors with the sampling rate 250Hz. An ECG cycle is considered as one hundred data before the peak and two hundred data after the peak.



(Figure 8) The ECG signal

2. ECG Cycle Modeling

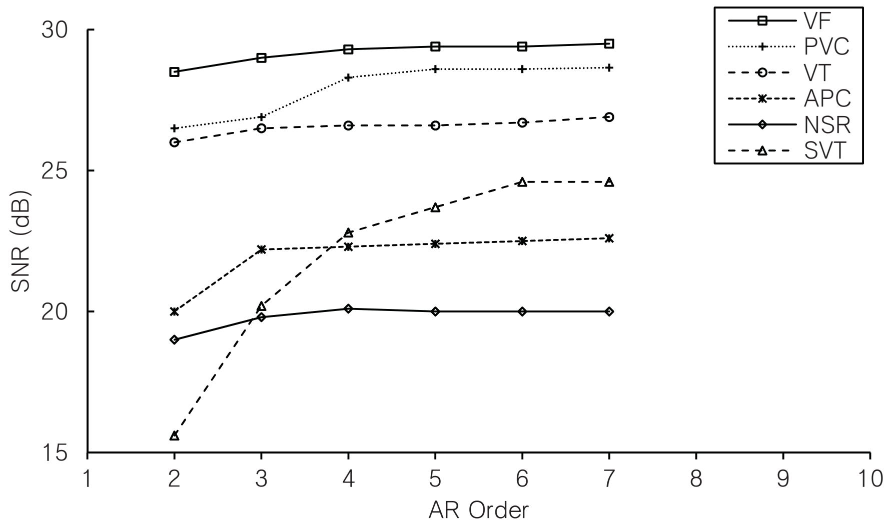
Most of the clinically useful information in the ECG is found in the intervals and amplitudes defined by its features such as characteristic wave peaks and time durations. Therefore, the development of accurate and quick methods for ECG feature extraction is of great importance and it is necessary for further classification of the signal in order to detect abnormal beats. In another word, extraction of parameters based on the ECG cycle provides fundamental features to subsequent classification. Moreover, the accuracy and efficiency of the modeling directly affect the diagnosis results.

The Autoregressive (AR) model is a generative model in the sense that the current value of the time series is generated as a linear combination of previous values [69]. It is simple and suitable for real time application. Actually, it has been used in various applications including modeling of EEG signals [70]. AR modeling can adapt for extracting good features from ECG signals, thus enabling the discrimination of certain ECG arrhythmias. In our current study, the AR model is used to model the ECG signal and generate the AR coefficients reflecting the shape, and duration characteristics of the ECG cycle. AR model is given by

$$X[t] = \sum_{i=1}^{N} a_i x[t-i] + \varepsilon[t] \qquad (1)$$

Where $X[t]$ represents 300 data series of one cycle, a_i is the AR coefficients, $\varepsilon[t]$ is zero mean white noise, and N is the AR order. A very important issue in AR modeling is the AR order used to model a signal. A proper AR order is critical to model a signal with sufficient accuracy for classification. As mentioned in [71], various model orders are used to estimate the accuracy of different ECG signals and the criteria used for the order selection is signal-to-noise ratio (SNR) given below.

$$SNR = 10\log\frac{\sum_{i=1}^{N}[v(i)]^2}{\sum_{i=1}^{N}[v(i)-\tilde{v}(i)]^2} \qquad (2)$$



(Figure 9) SNR for various AR model orders

Where $v(i)$ and $\tilde{v}(i)$ are the original and simulated signals. An AR order chosen as 4 is enough to model the ECG signal (see Fig. 9). They proved that with AR order four, the computed parameters are good enough to achieve accurate modeling. Furthermore, the signal to noise ratio increases initially with model order, but remains almost constant for AR orders greater than or equal to four. In addition, computing the AR coefficients of higher orders would increase the number of computations.

The AR coefficients are estimated using burg's algorithm [72] with the AR order 4. The burg's algorithm does not directly estimate the parameters, but instead it recursively estimates reflection coefficients, which is given as

$$\mu = \frac{-2\sum_{n=0}^{N-k-1} f_k(n+k+1)b_k(n)}{\sum_{n=k+1}^{N} f_k(n)^2 + \sum_{n=0}^{N-k-1} b_k(n)^2} \tag{3}$$

Here $f_k(n)$ is the forward prediction error and $b_k(n)$ is the backward prediction error. N refers to the length of the data series. Then, the AR coefficients matrix can be calculated based on the reflection coefficients by applying the Levinson−Durbin recursion [73].

$$A_{k+1} = A_k + \mu V_k \tag{4}$$

Here $A_k = [1 \;\; a_1 \;\; a_2 \;\; \cdots \;\; a_k]'$, is a column vector of AR coefficients and V_k is an inverted order vector of A_k.

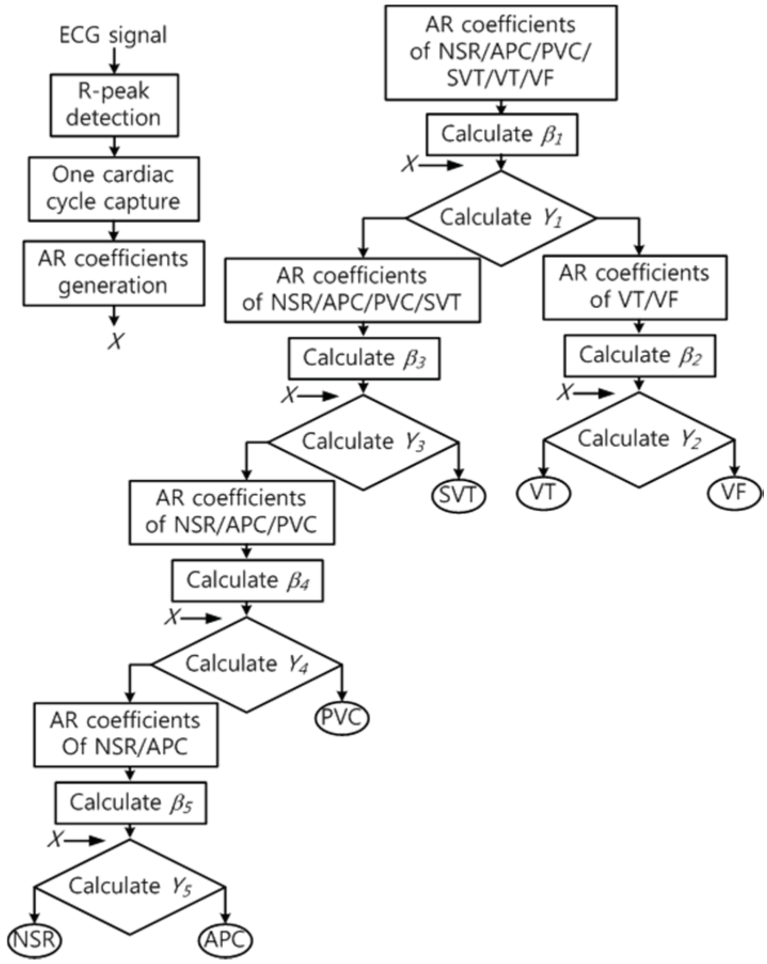
3. ECG Cycle Classification

The classification of the ECG cycle into different physiological disease categories is a complex task. Computer based classification of the ECG can achieve high accuracy and offers the potential of affordable mass screening for cardiac abnormalities. Successful classification is achieved by discriminating effectively among the required diagnostic categories.

In our study, after deriving AR coefficients based on one ECG cycle, ECG classification is performed to categorize this ECG cycle. Many algorithms for ECG classification have been developed in prior work achieving very good performance, such as Generalized Linear Model (GLM) based method while none of them is aimed at resource limited sensor nodes in BANs. Our Euclidean Distance (ED) based method designed for BANs simplifies the computation complexity by only performing a one-stop classification while still possessing high enough classification accuracy.

a. Generalized Linear Model based Method

GLM based classification is performed to differentiate a normal ECG cycle from those of the other five cardiac diseases – Atrial premature contraction (APC), Premature ventricular contraction (PVC), Superventricular tachycardia (SVT), Ventricular tachycardia (VT), and Ventricular fibrillation (VF) in several steps. In each step, GLM based classification includes two stages. Fig. 10 shows the working flow of this algorithm.



(Figure 10) Flow chart of GLM based classification method

In the first stage, estimator β is computed as

$$\beta = (A'A)^{-1} A'Y \tag{5}$$

Where A is a matrix of AR coefficients, each row maps to one specific ECG cycle type out of six observed categories. Y is the response matrix representing the attribute of each category (belong to or not belong to). It is a column vector consisting of 1 (belong to) and −1 (not belong to) in each row. β is calculated in each step of the classification. In the second stage, the output response is calculated as follow

$$Y_i = X\beta \tag{6}$$

Where X is a row vector consisting of tested ECG signal AR coefficients obtained from AR modeling. Y_i is the response of i−th step. β is the estimator calculated in the first stage. In each step, test ECG cycle is classified based on the sign of Y_i. The total computation load is high, including floating point matrix transposition, inversion, and multiplication.

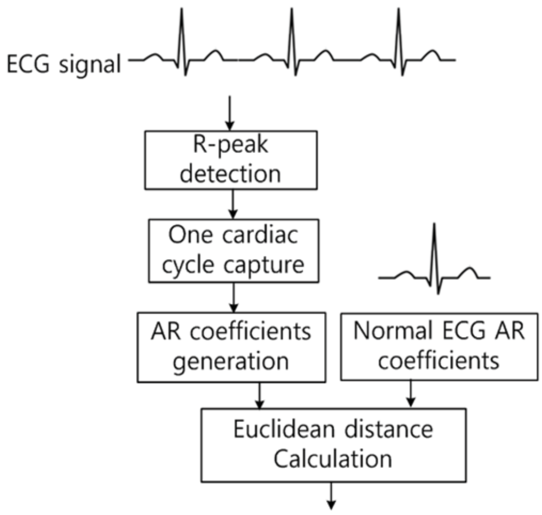
```
if (Y1 > 0)
    if (Y3 < 0)
        then SVT cycle
    else if (Y4 < 0)
        then PVC cycle
          else if (Y5 < 0)
              then APC cycle
                else NSR cycle
else if (Y2 > 0)
    then VT cycle
      else VF cycle
```

(Figure 11) Pseudo code of GLM classification

Based on the obtained AR coefficients, GLM based classification works like this: In the first stage Y_1, the tested ECG cycle is classified as belong to two classes, one containing NSR, APC, SVT, and PVC, and the other containing VF and VT. In the second stage Y_2, VF and VT are distinguished between each other. Then, SVT cycle is differentiated in stage Y_3 and PVC cycles are distinguished in stage Y_4, finally, in stage Y_5, the normal cycles and APC cycles are differentiated. Fig 11 shows the pseudo code for GLM based classification.

b. Euclidean Distance based Method

Our ED based classification method categorizes ECG cycles into abnormal or normal instead of specific cardiac diseases by computing the Euclidean distance of AR coefficients between test ECG cycles and normal sinus rhythm cycles (see Fig. 12).



(Figure 12) Flow chart of ED based classification method

The Euclidean distance d between AR coefficients of current test ECG cycle A=(a_1, a_2, ⋯, a_n)and normal ECG cycle B=(b_1, b_2, ⋯, b_n) is calculated as

$$d = \sqrt{(a_1 - b_1)^2 + (a_2 - b_2)^2 + \cdots + (a_n - b_n)^2} \tag{7}$$

Each time one ECG cycle is located, the sensor node performs ECG analysis and determines whether this sampled cycle is abnormal or not. Only those cycles that deviate significantly from the standard normal cycles are reported to base station. A threshold δ is defined as the worst-case deviation that can be tolerated. Therefore, if the actual calculated distance d between real time cycle and the reference cycle is larger than the threshold δ, communication is initiated between the sensor node and the base station to inform the occurrence of abnormal ECG cycles. Computation of d only involves a few floating point subtractions, multiplications and square root operations.

C. Prioritized MAC Protocol over BAN

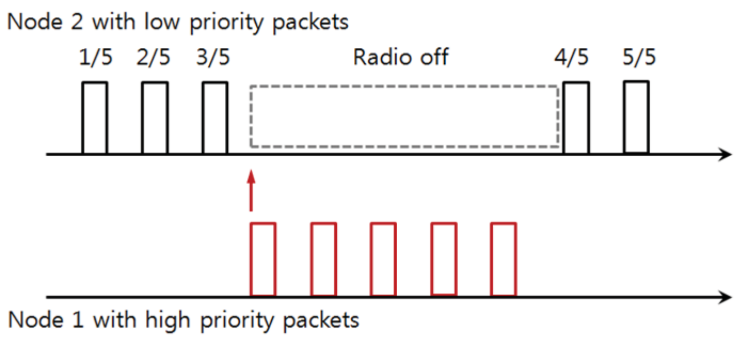
1. Reliability Issues in Intelligent Sensor Node based BANs

An important characteristic of the intelligent nodes based BAN system is that packets delivered in the network are always with different levels of significance. Some are life threatening and some are just network maintaining packets. Furthermore, the monitored parameters also have different health urgency levels on the patient's life, such as the ECG abnormality signal and the body temperature. The delay of reporting ECG abnormality signal can lead to changes in a patient's physical appearance and even death. The reliable and timely delivery of emergency information is more critical than energy efficiency for the MAC layer in such a situation. Therefore, in order to guarantee the reliable and timely delivery of critical information, different access priority levels for sensor nodes in the BAN based system should be provisioned. Urgent packets containing life threatening information should be delivered with higher priority. Thus, the design of uncomplicated prioritized MAC protocols is the main challenge to ensure the reliable and timely transmission of the abnormality signal with limited battery capacity of sensor nodes.

Furthermore, the delivery of abnormal signal usually comes as burst traffic. For example, in the ECG monitoring case, an ECG cycle consists of 300 sampled ECG data at the sampling rate of 250 Hz. Assuming 10 data per packet, 30 packets can cover an ECG cycle, in other words, only if the 30 packets are successfully transmitted, can the doctor check the intact abnormal ECG cycle in details. The faster these 30 packets being transmitted, the sooner the doctor can diagnose the heart disease and give treatment. Therefore, the transmitting of this abnormal ECG cycle is like suddenly injecting burst traffic into the network. We are aiming to ensure that the urgent packets delivered in this burst traffic are reliably and timely transmitted to the receiver.

2. Prioritized MAC Protocol

To provide differentiated quality of service and ensure the reliable delivery of urgent messages, the MAC protocol must provide effective mechanisms to support differentiated priority messages, such that high priority messages can be transmitted in preference to low priority messages. The basic mechanism can be seen in Fig. 13.



(Figure 13) Prioritized medium access scheme

If a sensor node has data to send, it first performs clear channel assessment t o ensure that no other node is transmitting at that moment. If the channel is clear, the sensor node will transmit this packet and wait for the acknowledgement from the receiver to make sure the packet is received correctly or it will retransmit the packet immediately. If the channel is not clear, the sensor node will start a congestion backoff and sense the medium later. The shorter the congestion backoff is, the more chance for the sensor node to be able to access the medium. Therefore, high priority messages always have shorter congestion backoff time and low priority messages have to wait a longer time before sensing the medium again. If a sensor node receives a packet during the listen phase, the priority level of this packet should be checked. If the priority is higher than the message in the transmission buffer, the sensor node ceases its own transmission, enters a quiet phase automatically, and recovers after a certain amount of sleeping time.

An ECG cycle consists of 300 sampled ECG data at the sampling rate of 250 Hz. Assuming 10 data per packet, 30 packets can cover an ECG cycle. That means if an abnormal ECG cycle is reported, the low priority node has to wait more than [(1/250)*10 + packet interval]*30 ms, then, it wakes up automatically. For other physical signals, the sampling frequency and cycle length are different. So the calculated quiet time is different. Using this method, we can approximately evaluate the quiet time. If the low priority node waits too short, it will wake up during the transmission of the high priority packet. If the quiet time is too long, the low priority node may delay its own transmission for nothing. Fig. 14 shows the pseudo code for our proposed schemes.

This scheme ensures that sensor nodes with high priority packets have a higher possibility of gaining access to a busy channel to transmit its urgent packets. Furthermore, during the transmission, other nodes keep quiet automatically as soon as they receive the first high priority packet. In our scheme, the sender may only face contention at the transmission of the first packet. After that, the following packets can be transmitted without any disturbance. It is evident that the urgent messages with high priority are guaranteed to be transmitted to the receiver in this way.

```
For each sensor node, if the receive-event is triggered
if (the priority level of the received packet > the
priority level of the currently transmitting packet)
    Quiet flag = 1
    Turn off the radio component
    Start a sleep timer
For each sensor node, if the timer-fired event is triggered
If Quiet flag = 1
    Turn on the radio component
    Quiet flag = 0
Recover transmission of packets in the buffer
```

(Figure 14) Pseudo code of prioritized MAC protocol

IV. Experimental Results

A. Simulation Tools and Implementation

ECG monitoring application programs are written and compiled in NesC [74] on TinyOS [75]. Power consumption is estimated using PowerTOSSIM [76], which is a power modeling extension to TOSSIM [77] simulator in TinyOS. The power consumption is measured for five components - CPU, RADIO, LED, SENSOR, EEPROM.

TinyOS is an embedded component−based operating system, comprising a set of cooperating tasks and processes. It is written in NesC, which is a dialect of the C language optimized for the resource limited sensor node.

TOSSIM is a discrete event simulator for TinyOS sensor networks. Instead of compiling a TinyOS application for a mote, we first compile it into the TOSSIM framework, which runs on a PC. In this way, we can debug, test, and analyze algorithms in a controlled and repeatable environment. Original TOSSIM does not model power draw or energy consumption. However, it is feasible to add annotations to components that consume power to provide information on when their power states change. With the information of a power model to these transitions of each component, the overall energy consumption can be calculated. PowerTOSSIM is a complement of TOSSIM in power consumption evaluation with the implement of CPU cycle counter module.

In PowerTOSSIM, energy consumption is mainly measured of five components: CPU, RADIO, LED, SENSOR, EEPROM. Power state of each component of the simulated mote is tracked and logged to a trace file. To determine the energy consumption of each component per node, a power model is also included, which specifies the current of each working state of sensor nodes. The energy consumption of each component is calculated by

$$P = \frac{time \times voltage \times current\ of\ each\ state}{frequency} \tag{8}$$

Where *voltage* is taken as 3V power supply; *Current* of each work state is specified in [76] generated by real hardware experiments with sensor nodes as shown in Table 1; *time* is the time duration of each state that sensor node stays and it is expressed in cycles.

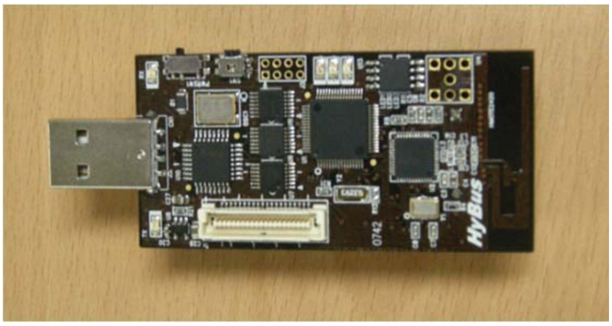
(Table 1) Current for different power modes

Mode	Current(mA)
CPU_Active	8.0
CPU_Idle	3.2
LEDs	2.2
Radio_Rx	7.03
Radio_Tx	8.47
Sensor board	0.69
EEPROM_Read	6.24
EEPROM_Write	18.4

To validate PowerTOSSIM's simulated energy consumption, we run the ECG monitoring application both on PowerTOSSIM and on an actual mote. The ECG monitoring application used here is the continuous monitoring scheme, in which sensor mote continuously transmits sensed data to base station without ECG cycle processing.

The real sensor node used is the Hybus mote [78], which consists of a MSP430 processor, a 2.4GHz CC2420 radio, and 512kB EEPROM as shown in Fig. 15. The sampling rate is 250 Hz. Sensor nodes and base stations communicate wirelessly through the embedded antenna integrated in sensor nodes.

X4-LIFE Inspector II [79] is used to measure the power consumption of the real mote. Considering the overhead of using this power meter, numerical processing is done to remove this measuring overhead to obtain the power consumption of the sensor node.



(Figure 15) Hybus mote

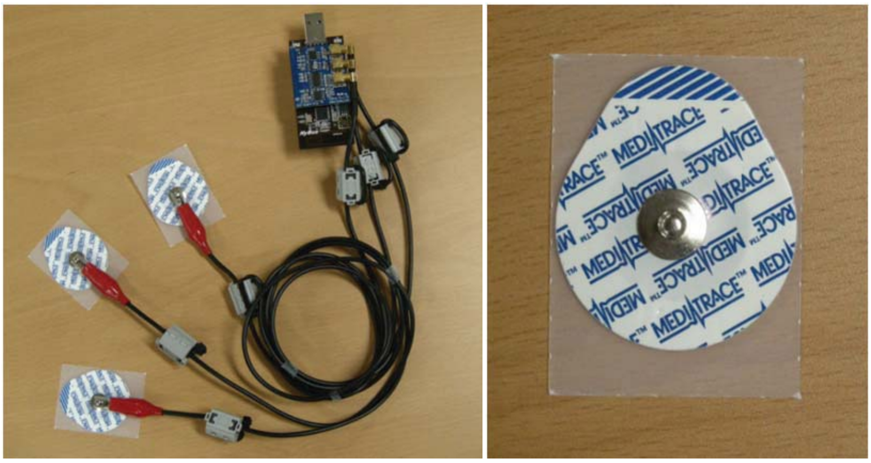
(Table 2) Total energy consumption: simulation results vs. measured data

Time (s)	Total Energy Consumption (mJ)		
	Simulated	Measured	Error (%)
60	2304.57	2403.51	−4.1
120	4706.87	4807.02	−2.1
180	7075.21	7210.52	−1.9
240	9580.77	9614.03	−0.3
300	12389.08	12017.54	3.1
600	24679.76	24035.08	2.7
900	37007.44	36052.62	2.6

Table 2 presents total simulated and measured energy consumption of continuous ECG monitoring application for various running time. As the table shows, PowerTOSSIM achieves excellent accuracy, with a near−zero average error compared to the real mote, and a maximum error of about 4.1%. Some of this difference between simulated and measured power can be attributed to instrumental error and noise. Other differences may be due to rounding errors in experimental setup.

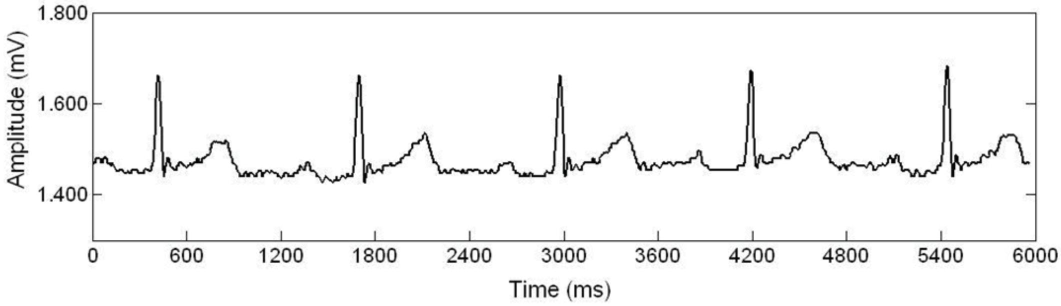
B. Simulation Results of the On Node ECG Analysis Algorithm

We begin the evaluation by checking the communication between the sensor node and the base station. For the ECG acquisition, a sensor board with three attached electrodes is used as shown in Fig. 16.



(Figure 16) ECG node and a single use electrode

Fig. 17 exhibits the ECG signal on the base station received from the sensor node. Characteristics of the ECG wave can be obviously seen in our received ECG signal. The sensor node without ECG analysis function always transmits the ECG signal as soon as it is detected. As transmission is frequently needed, the power consumption of power-hungry radio transceiver is greatly increased. Our evaluation centers on two issues: power consumption of the sensor node and classification accuracy of the ECG analysis algorithm.

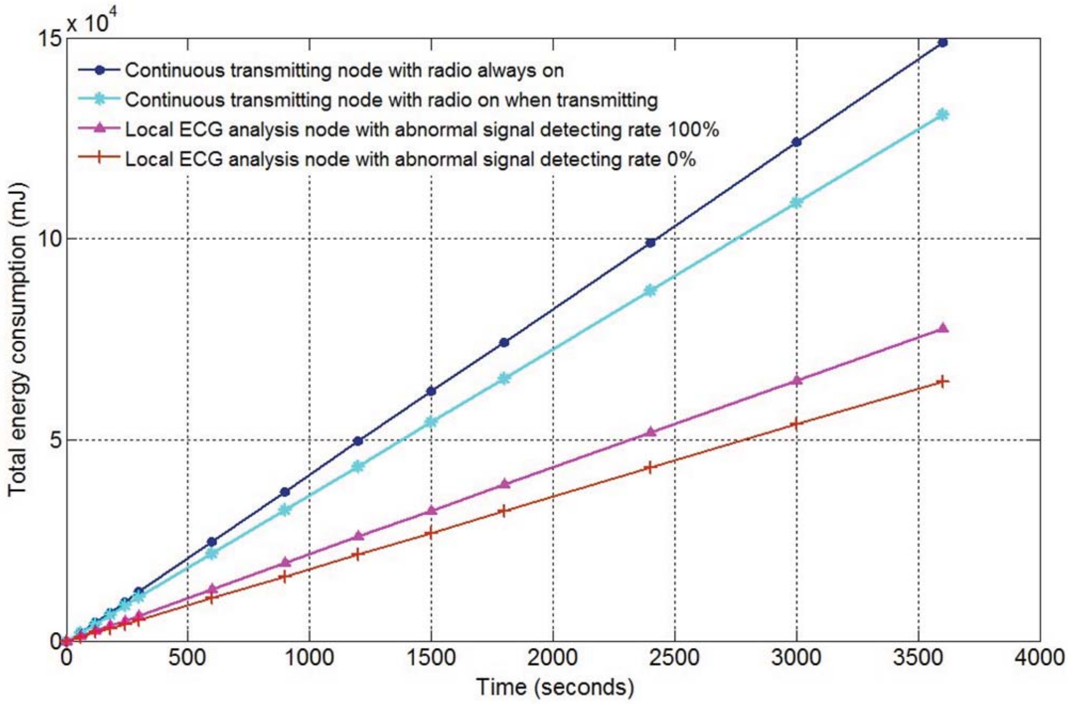


(Figure 17) ECG signal received at the base station

1. Power Consumption Results and Evaluation

For the power consumption issue, first we present power evaluation results obtained by varying the simulation time. We study four cases for the sensor node: continuously transmit ECG signal to the base station with radio always on; continuously transmit ECG signal to the base station with radio on only when transmission is required; perform ECG analysis locally with every detected ECG cycle as abnormal cycle; perform ECG analysis locally with every detected ECG cycle as normal cycle.

In the first case, the sensor node initiates all its components when it is put into monitoring. In the second case, the sensor node doesn't initiate the radio component at the very beginning. The transceiver is turned on when packets are ready and needed to be transmitted. Both of these two cases belong to the continuous transmitting scheme. The last two cases are on-node processing schemes. The only difference is whether abnormal ECG cycle is detected or not. The estimated total energy consumption of the proposed local processing sensor node and the sensor node performing continuous transmission is shown in Fig. 18.



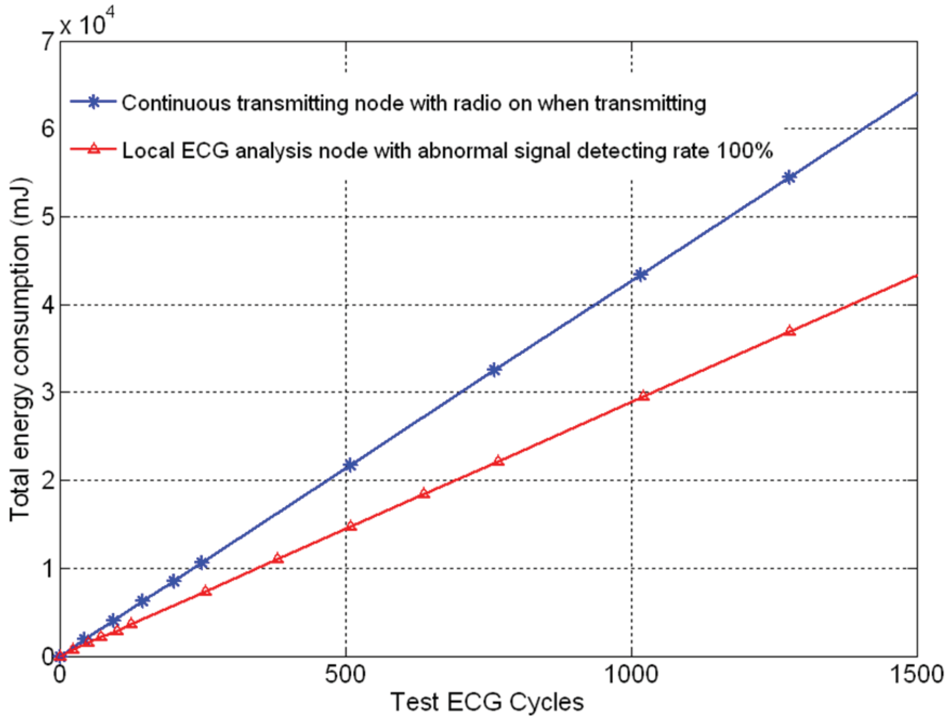
(Figure 18) Total energy consumption: Local ECG analysis node vs. Continuous transmission node

The horizontal line in the figure denotes the total accumulated energy consumption of each simulation time duration with different schemes mentioned above. The total energy consumption of the proposed local processing sensor node is reduced significantly comparing to the traditional sensor node without local ECG analysis function. In our proposed system, storing ECG data performed by EEPROM component and ECG analysis performed by CPU component slightly increases the energy consumption, while Radio transmission is not always necessary and accordingly the Radio component energy consumption is greatly reduced. This figure also shows that the longer the monitoring time, the more the power can be saved.

Let us take a close look at the energy consumption of each component in Table 3 as well. The data is captured after analyzing one hour-long ECG signals. It shows that the proposed scheme trades computation for transmission. The proposed system is more energy efficient and it saves about 57% energy for the best case and the local ECG analysis node will achieve longer lifetime. In Fig. 19, Scheme B and Scheme C are further analyzed with the energy consumption of different cycles. For analyzing one cycle in Scheme B, the energy consumption of computing sub-system increases, while the energy consumption of the communication sub-system decreases, comparing to Scheme C. This results in the decrease of total energy consumption per cycle by up to 33%.

(Table 3) Energy consumption: Local ECG analysis node vs. Continuous transmission node

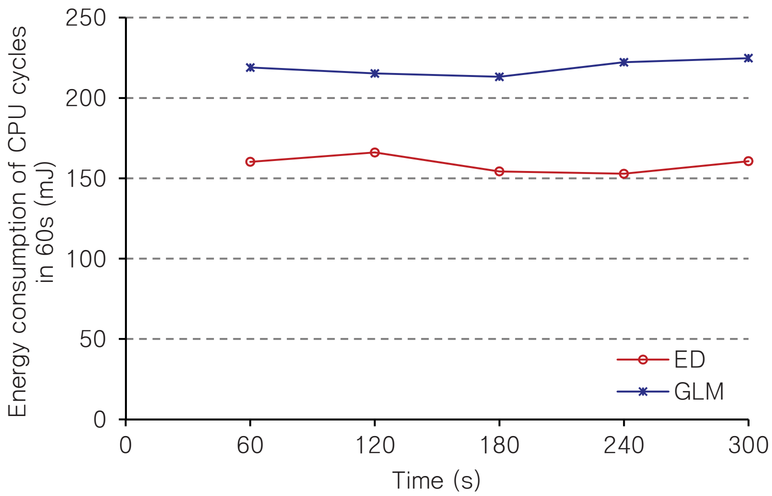
Components	Energy Consumption (mJ)			
	A	B	C	D
CPU	44565.1	44511	54345.5	54295.5
RADIO	84848.2	67009	1115.4	0
LED	11869.6	11855.2	11859.3	0
SENSOR	7445.5	7436.5	7440.5	7435.1
EEPROM	0	0	2840.6	2833.5
TOTAL	148728.4	130811.7	77601.3	64564.1



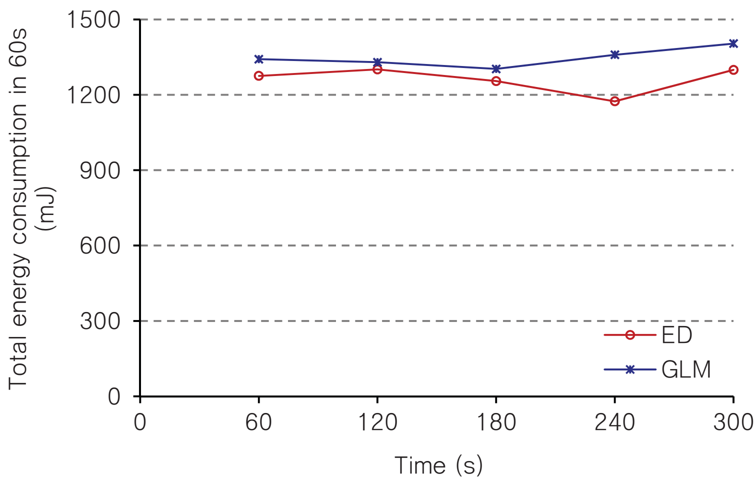
(Figure 19) Total energy consumption with different cycles

In Fig. 20, energy consumption of CPU cycles for ED and GLM based classification methods at intervals of 60s is observed. Obviously, there is a certain gap of energy consumption between these two schemes and ED based method saves much more energy when compared with GLM based method. On average, the CPU cycle energy consumption in every 60s of using ED based method is 158.84mJ, while it is 218.88mJ of using GLM based method. Energy consumption in 60s is reduced by up to 31.21% by using ED based classification method.

In Fig. 21, total energy consumption includes five parts: CPU, RADIO, LED SENSOR, and EEPROM. Experimental result shows that the total energy consumption difference of ED and GLM methods is smaller than that of the CPU cycles. Energy consumption of ED based method can be reduced at most 13.63% in 60s when compared with GLM method.



(Figure 20) Energy consumption of CPU cycles in 60s



(Figure 21) Total Energy consumption in 60s

This is due to the computation delay of GLM based method. Specifically, in each cycle, The GLM based method requires more time to finish ECG analysis. Therefore, the total number of ECG cycles that can be used for diagnosis is smaller than using ED based method in specific time duration, and accordingly the energy consumption of other components such as RADIO is smaller than using ED based method which leads to a decrease in total energy consumption. In other words, GLM based method results in smaller energy consumption gap with ED based method in a specific time interval, since a smaller number of ECG cycles are processed. This processing delay of GLM based method postpones the time of detecting any possible abnormal ECG cycles, which may lead to loss of the best treatment timing.

2. Diagnosis Accuracy Results and Evaluation

For the diagnosis accuracy issue, we adopt test data set from MIT-BIH malignant ventricular ectopy database, Sudden cardiac death holter database, and QT database of PhysioNet [80]. PhysioNet is an online forum for dissemination and exchange of recorded biomedical signals. The PhysioBank currently includes databases of multiparameter cardiopulmonary, neural, and other biomedical signals from healthy subjects and patients with a variety of conditions including sudden cardiac death, congestive heart failure, epilepsy, gait disorders, sleep apnea, and aging. Normal sinus rhythm (NSR), APC, PVC, SVT, VT, and VF cycles are acquired from these databases for ECG modeling and classification. Table 4 shows the AR coefficients for normal ECG cycles and those of various cardiac diseases.

(Table 4) AR coefficients for ECG classes

Classes	a(1)	a(2)	a(3)	a(4)
NSR	−2.477	2.430	−1.188	0.263
APC	−2.090	1.492	−0.227	−0.129
PVC	−2.005	0.870	0.412	−0.272
SVT	−1.946	1.204	−0.301	0.093
VT	−2.181	1.529	−0.407	0.065
VF	−1.090	−0.148	0.209	0.061

(Table 5) Classification results of GLM based method

Test cycles	Classification results					
	NSR	APC	PVC	SVT	VT	VF
NSR	106	1	0	9	1	1
APC	14	81	4	18	1	0
PVC	0	3	106	1	7	1
SVT	0	0	1	117	0	0
VT	0	0	4	0	113	1
VF	0	0	0	41	12	65

The classification results of GLM and ED based method are shown in Table 5 and Table 6. The GLM based method is tested with 118 NSR cycles, APC cycles, PVC cycles, SVT cycles, VT cycles, and VF cycles each, which are obtained from databases mentioned above. Rows are classified by test cycles and columns are categorized by classified diseases. For example, GLM based method classifies 118 NSR cycles as 106 NSR cycles, 1 APC cycle, 9 SVT cycle, 1 VT cycle, and 1 VF cycle. The ED based method is also tested using the same test sets but only classifies them as normal or abnormal with classification threshold 1.0.

(Table 6) Classification results of ED based method

Test cycles	Classification results	
	Normal	Abnormal
NSR	112	6
APC	17	101
PVC	5	113
SVT	0	118
VT	17	101
VF	0	118

The classification accuracy comparison of GLM and ED based methods is shown in Table 7. For GLM based method, the accuracy of detecting NSR, APC, PVC, SVT, VT, and VF cycles vary from 55% to 99%. For ED based method, the accuracy of detecting normal and abnormal cycles is higher than 86%. Experimental results show that ED based one-stop method is efficient in distinguishing abnormal cycles from normal cycles, which is critical for sensor nodes with ECG analysis function.

Comparing to the simulation results of the GLM based method in prior work [71], the accuracy for SVT and VT cycle is very close. But the accuracy for other cycles is different. This is due to two reasons: i) The used test data base is different. They use data from the MIT-BIH arrhythmia database, the MIT-BIH ventricular arrhythmia data base and the MIT-BIH supraventricular arrhythmia database. ii) We use simple peak locating method to find one ECG cycle considering the resource limited sensor node. They use a more complex method Pan-Tompkims algorithm [81] including filter, differentiator, squaring operation, and moving window integrator.

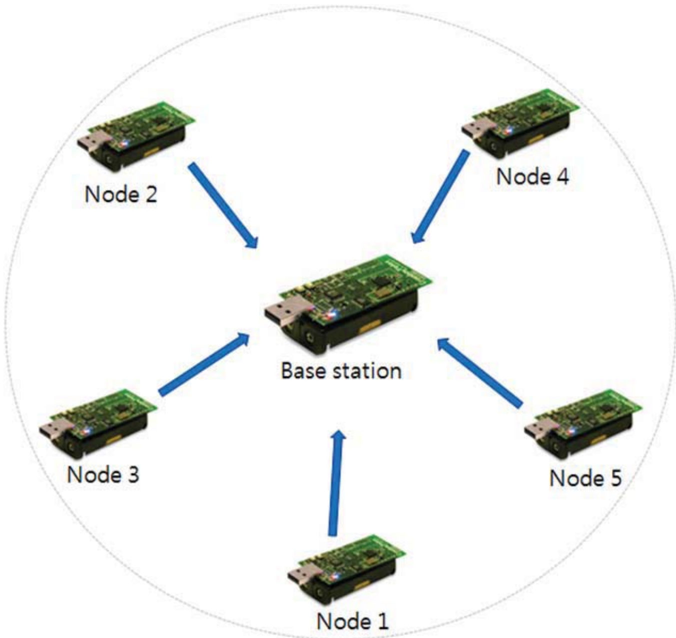
(Table 7) Classification accuracy comparison: ED based method vs. GLM based method

Methods	Test cycles					
	NSR	APC	PVC	SVT	VT	VF
GLM	90%	69%	90%	99%	96%	55%
ED	95%	86%	96%	100%	86%	100%

C. Implementation of the Prioritized MAC Protocol

1. Network Settings

For performance analysis, the star topology is adopted, consisting of five leaf nodes (node 1 ~ node 5), and a base station as shown in Fig. 22. All the nodes perform full listening which is the best case of ensuring reliable and timely transmission. Each experiment begins with switching on four leaf nodes (node 2 ~ node 5), and sending low priority packets as background transmissions. Next, randomly, the other leaf node (node 1) is switched on, transmitting 30 packets with high priority packets to the base station.

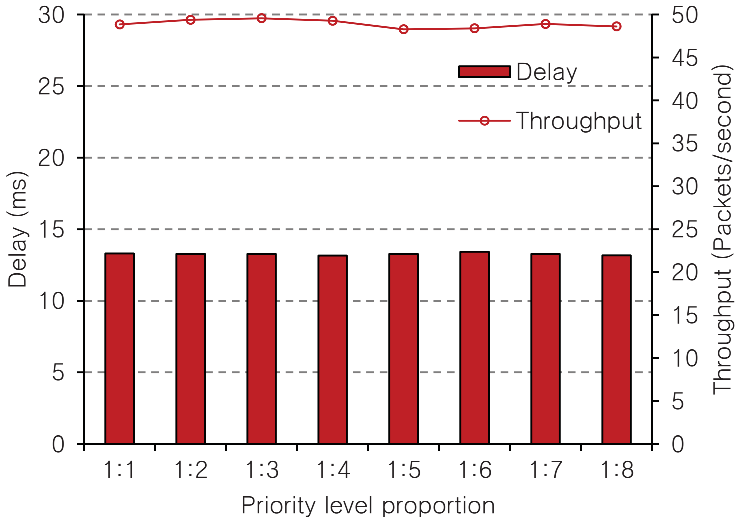


(Figure 22) Network topology

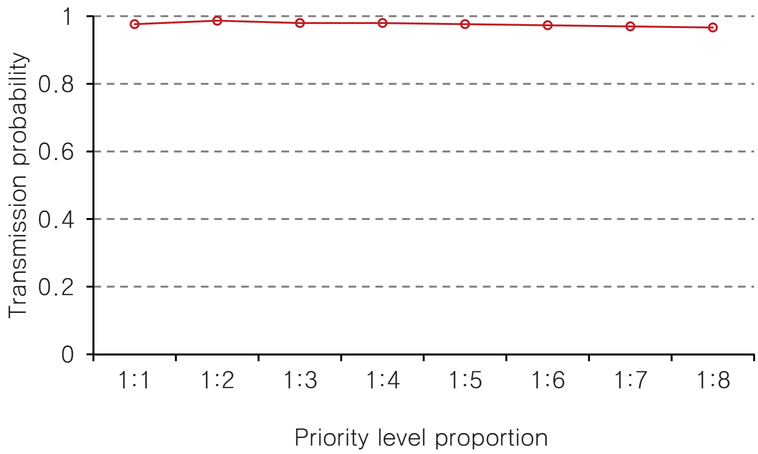
Experiments are done to evaluate the performance of the network with this burst traffic injection under different network circumstances. The packet transmission time and receipt time of node 1 are recorded in real time. The congestion backoff time of node 2 ~ node 5 is set to 0.3125ms, 0.625ms, 0.9375ms, 1.25ms, 1.5625ms, 1.875ms, 2.1875ms, 2.5ms and it is 0.3125ms for node 1 all the time. So the congestion backoff proportion of node 1 and node 2 ~ node 5 is 1:1, 1:2, 1:3, 1:4, 1:5, 1:6, 1:7, and 1:8. The measurement is repeated 10 times for each congestion backoff proportion and we also vary the packet interval to see the effect to the transmission delay, transmission probability and throughput. We compare our prioritized MAC protocol with full listening B-MAC (FL-BMAC) to see the specific advantages of our scheme.

2. Performance Evaluation

Fig. 23 and Fig. 24 show the results for different priority level proportions. Packets are transmitted at the fastest rate, with the packet interval as 0 ms. As the packets are usually related with patients' lives, they should be transmitted as soon as possible. Therefore, the packet interval 0 ms is the best case for the healthcare application. It is to send the next packet immediately after the previous one is sent. The transmission probability is analyzed with the maximum number of retransmissions as 0 (no retransmission at all), which means that the packets only have one chance to be sent or it will be dropped.



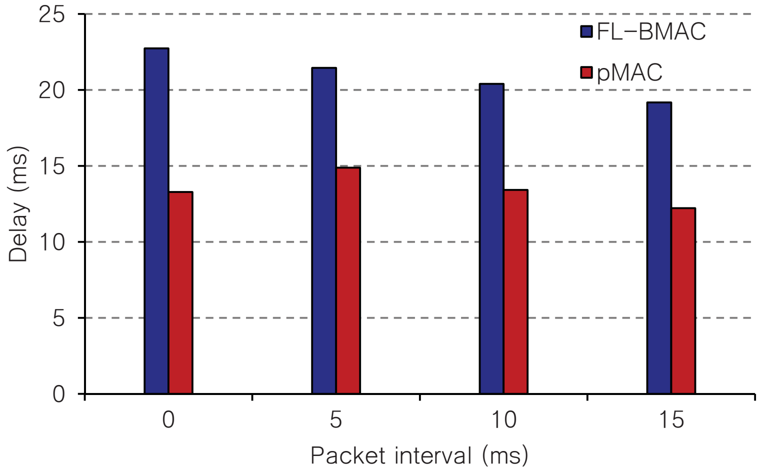
(Figure 23) Average packet delay and throughput with different priority level proportion



(Figure 24) Transmission probability with different priority level proportion

Since the channel is cleared for the critical node and there are almost no congestion backoffs used in pMAC. Collisions only occur at the beginning of the burst traffic with the 30 packets, so averagely their effect is very small. The average packet delay, throughput, and transmission probability of sending high priority packets can remain stable, whatever the priority level proportion is.

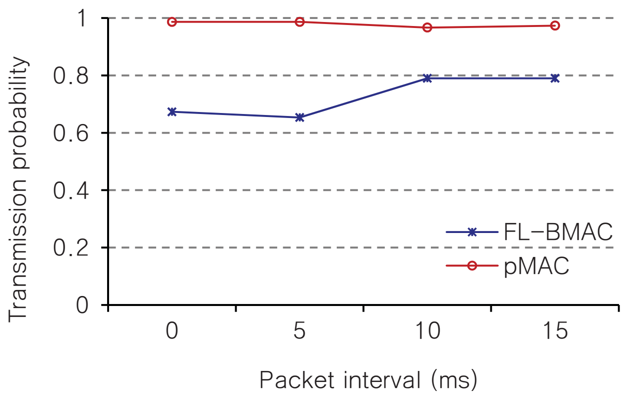
The average packet delay between the transmission time and acknowledged time with priority level proportion as 1:2 is shown on Fig. 25. Packets are transmitted at four different intervals: 0 ms, 5 ms, 10 ms, and 15 ms. The experimental results show that the average delay for high priority packets of the prioritized MAC protocol is much shorter than that of the full listening B-MAC. Furthermore, the latency of full listening B-MAC increases as the packet interval is shortened, while the delay of pMAC remains relatively more stable.



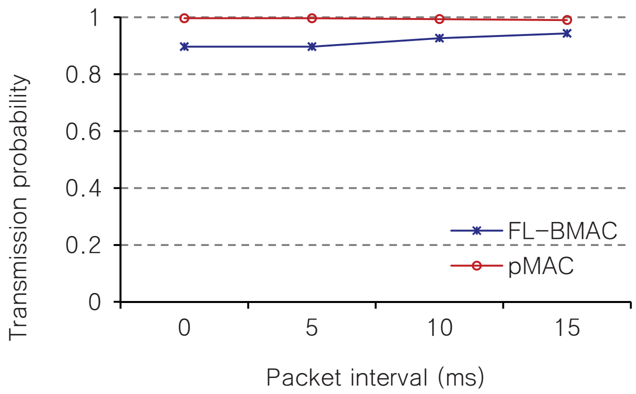
(Figure 25) Average packet delay with different packet intervals

The main reason is that the critical node with high priority packets does not need to contend for the medium all the time and congestion backoffs are only used at the beginning of the transmission contention. Up to 45% of the delay time is saved in this way. With the increase of the packet interval, the latency of pMAC only changes a little. Therefore, it is possible to adjust pMAC to accommodate other emergency packet delivery in the urgent packet transmission intervals, which shows the potential flexibility of our proposed scheme. This will not increase the current transmission packet delay according to the result shown in Fig. 25.

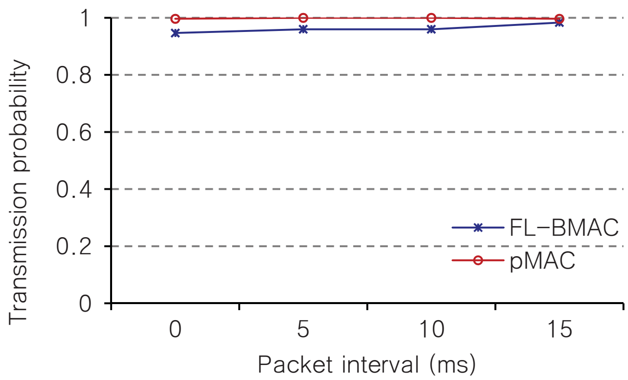
Fig. 26 shows the experimental results on transmission probability with priority level proportion as 1:2. We analyze our results by setting 3 maximum numbers of retransmissions: 0, 1, 2. Experimental results show that urgent packets in our prioritized scheme have a high transmission probability than in the full listening B-MAC. As shown in Fig. 26(a), with no retransmission, full listening B-MAC only achieves transmission probability of 79% at most, while it is above 97% for our scheme. This is because B-MAC treats all the packets the same when they access the medium and the critical node also has to contend like all the other nodes to gain access to the channel all the time. Retransmission of the urgent packets occurs frequently. However, in our proposed scheme, retransmission only occurs at the transmission of the first packet to make sure that all the other nodes are going to be quiet for a while. Moreover, the transmission probability of our scheme is stable and unaffected by the transmission packet interval.



(a) Maximum number of retransmissions = 0

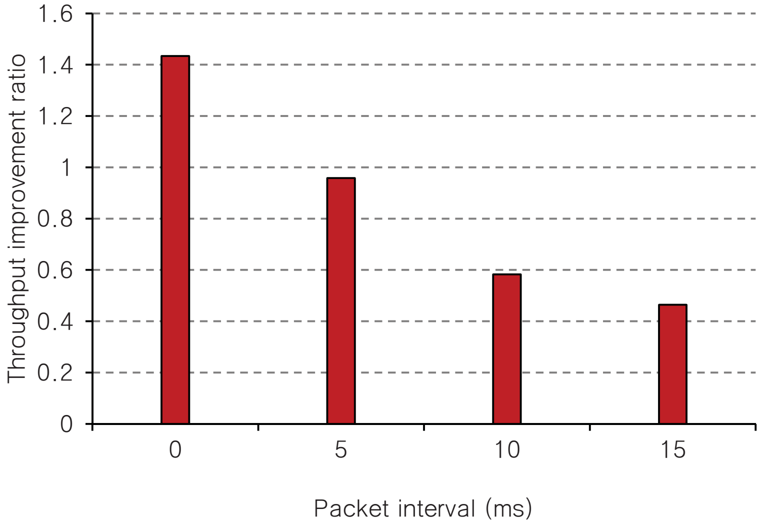


(b) Maximum number of retransmissions = 1



(c) Maximum number of retransmissions = 2

(Figure 26) Transmission probability with different packet intervals



(Figure 27) Throughput improvement ratio with different packet intervals

Fig. 27 depicts the measured throughput improvement ratio of our scheme with priority level proportion as 1:2, for node 1, comparing to full listening B-MAC. As packet interval gets shorter, the throughput of full listening B-MAC is relatively stable because the packet injection rate gets higher, and collisions and retransmissions occur frequently. Although the packets are transmitted with higher speed, the total number of transmitted packets within specific time duration doesn't increase much. While the throughput of pMAC increases significantly. The refore, the average throughput of prioritized MAC is increased by 46% at least an d this benefit can be further expanded as the packet interval gets shorter. We can achieve 143% throughput improvement with the packet interval of 0 ms, which is the favorable case for sending urgent message. This feature is significant in healthcare and medical applications because timely and completed signals ensure timely and correct diagnosis by doctors.

To sum up, our prioritized MAC protocol outperforms the full listening B-MAC in average packet delay, transmission probability and throughput. The high priority packet gains more transmission probability and lower packet delay by having shorter congestion backoff and experiencing fewer collisions through "quieting" other low priority nodes.

V. Conclusions and Future Work

In this thesis, we deal with an intelligent sensor node based ECG monitoring system over body area network. Our objective is to reduce the power consumption of the sensor node from the system working mechanism point of view and improve the reliability of sending urgent messages.

We start our research by analyzing the energy consumption distribution of traditional continuous ECG monitoring systems, in which the ECG signal has to be sampled, processed and transmitted to the base station all the time. We find that the transceiver component consumes most of the total energy consumption, so we derive the idea of trading computation for communication. Based on the on−node processing scheme, the communication overhead can be greatly reduced.

Then, we propose the light weight ED based ECG analysis algorithm to reduce energy consumption of the sensor node, which classifies tested ECG cycles only into normal or abnormal. In this way, monitoring is performed continuously, but transmission is not necessary all the time. Only when the tested ECG cycle is determined as abnormal by the ECG analysis algorithm, will radio transmission be initiated. From the detailed experiments and numerical illustrations we can see that our ED based algorithm is a simple, energy efficient and accurate analysis method which can be easily implemented and extended for resource limited sensor nodes of various healthcare monitoring applications.

Furthermore, we extend to include a prioritized MAC protocol to provide a reliable link for reporting critical information to the doctor. By prioritizing the packets based on their application urgency level and clearing the channel for critical packets, the possible life threatening message can be delivered with great efficiency and reliability. The experimental results show that this scheme with different medium access priority levels has better performance than full listening B−MAC in average packet delay, transmission probability and throughput.

In the near future, we plan to continue our research on intelligent sensor node based ECG monitoring system from the following aspects. First, we will study the energy consumption distribution of other different types of ECG analysis algorithms and consider improving the diagnosis accuracy of local ECG algorithm for sensor nodes. Second, we will introduce the prioritized medium access scheme to more complicated priority levels and include intra−node prioritization. Third, we also plan to implement this local processing scheme for other physiological parameter monitoring.

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ABSTRACT

On-Node Processing and Priority Aware Medium Access for Energy-Efficient and Reliable ECG Monitoring over Body Area Networks

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With the development of wireless communication, sensor design, and energy storage technologies, wireless sensor networks (WSNs) have become a reality. Currently, monitoring human body physiological parameters is an interesting application of WSNs. However, the well-designed WSNs are not ideally suited to these applications. For example, the power consumption of a sensor node should be reduced to the minimum to sustain long term monitoring, and the transmission reliability should be further emphasized with life threatening information delivered through the network. Therefore, it is necessary to develop a body area network

(BAN) to meet the needs of these healthcare applications with lower power consumption and reliable transmission. BAN based continuous monitoring systems have great potential for managing people's chronic health conditions. Many healthcare applications based on BANs have been researched, among which the continuous monitoring of people who are suffering from heart illnesses is the most remarkable. A BAN based ECG monitoring system allows doctors to pervasively monitor patients' heart conditions in any environment without any restriction of the patients' activities.

Energy efficiency is one of the biggest challenges to the ECG monitoring application of BANs, because the battery powered sensor node has very limited energy capacity. It cannot afford the long term monitoring by continuously sensing and transmitting the ECG signals to the doctor. However, the energy can be used in a more efficient way to prolong the life time of the sensor node. Thus far, there are three main ways for saving energy of the sensor node: low power hardware design, light weight software design, and smart working mechanism. Many efforts have been devoted to designing energy efficient hardware such as low power transceivers, processors, and software such as light weight MAC protocols and routing protocols. However, only a few works, either directly porting existing ECG analysis algorithms or simply measuring duration and amplitude of ECG signals, have been done from the system working mechanism point of view to save power consumption of the sensor node.

Our motivation is to use smart working mechanism of the sensor node for saving energy. We put some intelligence on the sensor node by trading computation for communication so that continuous transmission is not necessary all the time. In this work, we thoroughly analyze the power consumption of sensor nodes and setup the framework of an intelligent sensor node based ECG monitoring system. Then, we propose a light weight ECG analysis algorithm for local diagnosis, which achieves a sufficiently high classification accuracy and energy efficiency. The proposed ECG analysis algorithm classifies ECG cycles into normal or abnormal by computing the Euclidean distance between a tested ECG cycle and a normal ECG cycle. We also extend by including a prioritized MAC protocol to improve the reliability of reporting abnormal information. The prioritized MAC protocol is characterized by two features: i) It prioritizes packets by increasing the backoff time of non-urgent packets; ii) The channel is also cleared for the urgent packets by ceasing the transmission of all other non-urgent packets.

Moreover, we provide extensive experimental simulation and implementation results for validating the efficiency of these proposed schemes. The local ECG analysis algorithm is evaluated from two aspects – the power consumption and diagnosis accuracy. The prioritized MAC protocol is estimated from three aspects, namely, the average packet delay, the retransmission probability, and throughput. These results demonstrate the energy efficiency and reliability of the intelligent sensor node based ECG monitoring system.