

WIRELESS TECHNOLOGIES FOR E-HEALTHCARE

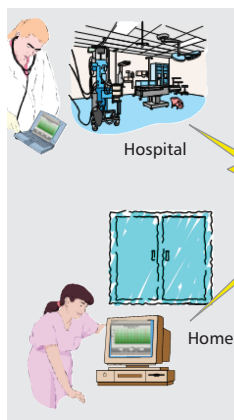
RESOURCE-AWARE SECURE ECG HEALTHCARE MONITORING THROUGH BODY SENSOR NETWORKS

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The authors propose a secure and resource-aware BSN architecture to enable real-time healthcare monitoring, especially for secure wireless electrocardiogram data streaming and monitoring.

ABSTRACT

Real-time medical data about patients' physiological status can be collected simply by using wearable medical sensors based on a body sensor network. However, we lack an efficient, reliable, and secure BSN platform that can meet increasing needs in e-healthcare applications. Many such applications require a BSN to support multiple data rates with reliable and energy-efficient data transmission. In this article we propose a secure and resource-aware BSN architecture to enable real-time healthcare monitoring, especially for secure wireless electrocardiogram data streaming and monitoring. A cross-layer framework was developed based on unequal resource allocation to support efficient biomedical data monitoring. In this framework important information (e.g., critical ECG data) is identified, and extra resources are allocated to protect it. Furthermore, BSN resource factors are exploited to guarantee a strict requirement of real-time performance. In this work we integrate biomedical information processing and transmission in a unified platform, where secure data transmission in a BSN proceeds with energy efficiency and minimum delay. In particular, we present a wearable ECG device consisting of small and low-power healthnode sensors for wireless three-lead ECG monitoring. Experimental and simulation results demonstrate that the proposed framework can support real-time wireless biomedical monitoring applications.

INTRODUCTION

Wearable health monitoring systems based on wireless body sensor networks (BSNs) offer many advantages over conventional health moni-

toring approaches. First, cables to the human body; thus, monitoring distance can be greatly increased. Second, a large number of sensors can be placed on patients if needed for real-time biomedical monitoring in either stationary or mobile scenarios. However, there is a significant gap in the current research activities on BSNs to meet the requirements of medical monitoring applications. In general, medical monitoring requires multiple data transmission rates, very high communication reliability, and relatively low transmission power. Traditional wireless in-network aggregations that fuse data from multiple end nodes may not be applicable in medical monitoring applications. The development of on-body information processing aims to reduce the total amount of data to be transmitted and increase transmission quality, which is demanded by BSN-based telemedicine applications. In error-prone wireless channels data loss in transmission is commonplace. However, most medical applications have a very strict requirement on lossless transmission of medical data. Any loss of important information in medical applications may lead to severe medical accidents and subsequent litigation issues. In order to ensure transmission quality for medical signals under limited power and computational resources, it is desirable to allocate resources unequally to protect more important information conveyed through wireless BSNs.

In this article we propose a secure and resource-aware BSN architecture enabling real-time healthcare monitoring, especially for secure wireless electrocardiogram (ECG) data streaming and monitoring. A cross-layer framework is developed based on unequal resource allocation to support biomedical data monitoring applications. In this framework important information (e.g., major ECG data) is identified, and extra resources are allocated to protect its transmission. Furthermore, BSN resource factors are exploited to guarantee a strict requirement of real-time performance. In this work we integrate biomedical information processing and transmission in one framework, where secure data trans-

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mission in a BSN proceeds with energy efficiency and minimum delay. Energy efficiency refers to savings in total energy consumption of medical sensors, healthnodes, and data terminals without degrading system performance. It is achieved through the energy-constrained signal quality maximization described later. In particular, we present a wearable ECG sensing system consisting of small and low-powered *healthnode* sensors for wireless three-lead ECG monitoring.

The rest of the article is outlined as follows. The next section reviews related work in the literature and highlights the contributions of this work. We then introduce the sensor nodes we developed for real-time ECG streaming and monitoring. We propose a BSN architecture that can meet the requirements for real-time health monitoring applications. We then present a secure resource-aware optimization scheme to achieve energy efficiency, reliable signal transmission, and information privacy. We evaluate the performance of the proposed architecture through both experiments and simulations. These results are compared with those of existing techniques, followed by the conclusions presented in the final section.

RELATED WORK

E-healthcare applications include physiological signal monitoring, diagnosis, rehabilitation, and treatment. Among these applications, we have seen some work that reported the use of wireless BSNs as a means of healthcare for patient monitoring. However, there are very few studies on system development for real-time health monitoring with wireless technology. Specific system developments reported recently include wristbands for measuring pulse, body temperature, galvanic skin reactions, and electromyography (EMG) data, and chest/arm belts for physiological monitoring. Vitalphone [1] was designed to record ECG data and transmit the data to a data center, enabling a diagnosis to be performed online or at a data processing center. Other commercial products (e.g., Sensatex, LifeShirt, and MagIC) utilize sensor arrays embedded inside garments for medical data collection. We have also seen some academic research (e.g., ACTis at the University of Alabama, BodyNets at UCLA) on detecting data using a body area network of sensors and route the data through a Wi-Fi-enabled PDA to the receiver. Some more recent studies [2–4] proposed an on-body wireless network architecture for health monitoring with reconfiguration capabilities to address challenging design issues such as power efficiency and reliability.

In terms of ECG data compression, most previous work focused on offline post-processing of ECG data for archival purposes. However, with wireless ECG medical applications, some research has been conducted to compress data through ECG source coding for real-time coding. They considered lossy compression algorithms due to the need for very high compression ratios. However, lossy compression can distort the ECG waveforms and may cause diagnostic and legal issues [5]. There are numerous ongoing research activities on the security of wireless

BSNs [6, 7]. Poon *et al.* [6] introduced a key distribution scheme in BSNs to achieve data protection. Bao *et al.* [7] utilized biometric signals such as interpulse interval (IPI) to authenticate the source data. In [8] the editors gave an overview of current wireless technologies trends in telemedicine, including retrieving medical data through BSNs. They suggested that emerging wireless technologies such as IEEE 802.15 and 802.16-based networks and security methods can be utilized in telemedicine systems for secure, reliable delivery of medical information and provision of health services. In addition, we have also seen several other existing reports on security issues in wireless sensor networks [9, 10]. However, these proposed approaches are typically more suitable for general applications of sensor networks, and may not be appropriate for applications in short-range ultra-low-power BSNs to support secure and reliable biomedical data transmission.

In this article we focus on the issues involved in implementing an efficient BSN platform to support medical applications. We propose a cross-layer framework for healthcare monitoring where the important medical information data are identified and protected using extra network resources (e.g., power and data rate), in order to balance energy efficiency and transmission quality. We also study the security issues related to medical healthcare applications. A resource-aware adaptive scheme is presented for selective encryption and compression to achieve secure data transmission with high energy efficiency in BSNs. Our approach can also contribute to reducing the overall delay of data transmission. In particular, we implement a wireless ECG device for real-time health monitoring called a *healthnode*, to demonstrate the feasibility of the proposed system architecture in real-time ECG monitoring applications.

HEALTHNODE AND WEARABLE ECG MONITORING

BSN ARCHITECTURE FOR HEALTHCARE MONITORING

The BSN architecture presented in this article includes several key components, as shown in Fig. 1. Several different types of medical sensors can be used in BSNs for different health monitoring purposes, as listed in Table 1. As described in Table 1, many different body sensors can potentially be used in healthcare monitoring applications. These sensors may work individually. They can also cooperate together to help achieve better healthcare services. For example, a foot pressure signal could also provide a physician with better understanding of ECG information. Future BSN healthcare monitoring devices should be able to accommodate these heterogeneous sensors.

Wireless healthnodes comprise the major element of the BSN architecture. A healthnode is a functional component that consists of a processing unit and a radio transmission unit with a sensor board and a local battery power supply or energy scavenge supply. We have implemented a

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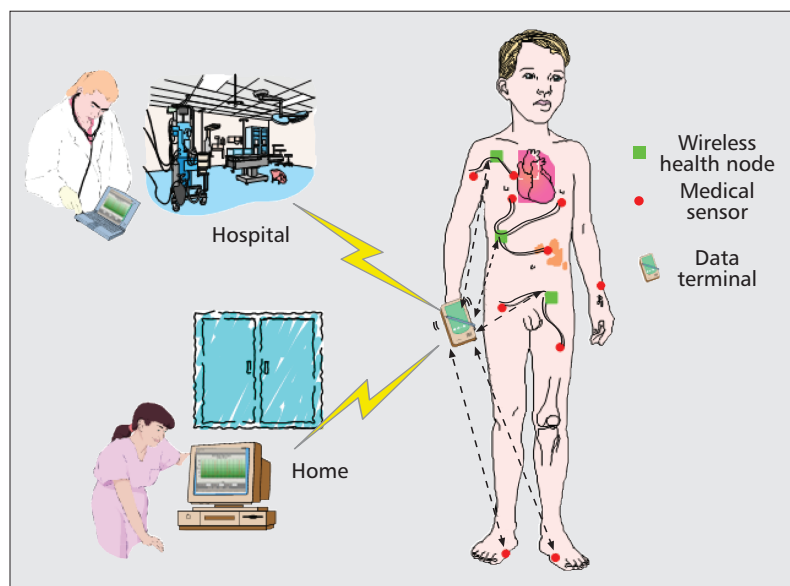


Figure 1. Healthcare monitoring system architecture.

healthnode in the wearable health monitoring system as shown in Fig. 2b. On the other hand, a data terminal provides the functionality of collecting the data from either medical sensors or healthnodes. It consists of a data processing unit and a data transmission unit. It may also have different radio interfaces with other types of wireless networks such as IEEE 802.11 and WiMAX. For example, a mobile phone and a PDA are typical data terminals.

This simple and generic BSN architecture can support many medical applications and accommodate different functional sensors. We have designed and implemented a wearable ECG real-time monitoring system that includes leads, healthnodes, and data terminals as shown in Fig. 1. ECG devices are the most widely used equipment in health monitoring applications. The BSN is organized hierarchically. Each medical sensor is wired or wirelessly connected to the healthnode, which processes the data and sends it to a data terminal such as a PDA. The PDA transmits the data to a machine at a physician's office using a wireless network such as IEEE 802.11 or GSM. Finally, the health data are sent to hospitals via wireless connections and the Internet.

A WEARABLE ECG MONITORING EXAMPLE

A physician may require continuous-time long-term ECG monitoring (e.g., the Holter ECG) for patients suffering cardiac arrhythmia, when an irregular heart rhythm occurs intermittently. Using traditional ECG systems in hospitals has several disadvantages. Most traditional ECG devices receive power from electrical outlets, and because they are usually heavy, they must be mounted on a cart and wheeled from one location to another. Patients must lie in bed and maintain limited mobility, and are usually bound to a prolonged hospital stay. In this scenario battery-operated sensors with energy scavenge capability and wireless networked units are particularly advantageous. Most existing ECG devices for patient monitoring (e.g., LifeSync [3]

and BioPatch [4]) are not very useful in mobile monitoring applications due to their large sizes.

Motivated by the aforementioned facts, we have implemented a healthnode ECG device as shown in Fig. 2b. This device is significantly smaller than most traditional ones and features a longer transmission range. The size of the ECG device, as shown in Fig. 2b, is comparable to that of a U.S. quarter coin. The approximate size is $3 \times 7 \times 2 \text{ cm}^3$. The size can be significantly reduced since the current battery case occupies the most area. The device could be as small as a business card if a thin and expensive battery is used. The transmission range is about 100 m. It uses a three-lead system and can serve for continuous ECG data monitoring purposes. It is more flexible than existing solutions because of its modular structure, which can be configured and reconfigured readily. For example, a mote-based patient allocating system can be seamlessly integrated into existing networks.

Several challenges must be tackled in order to design a practical wearable ECG device based on BSN technology. One of the most difficult problems is to implement a small and inexpensive ECG amplifier by finding an effective way to eliminate low-frequency noise (e.g., 60 Hz *hum*) without using bulky filters. Another challenge is to prolong battery lifetime, which should last weeks, by using lightweight and inexpensive batteries. A large, heavy battery should not be used in a device designed to be worn by patients conveniently and comfortably, and thus minimizing average power dissipation is the key. In addition, the ECG device should work compatibly with standard wireless protocols in order to facilitate its integration into existing hospital network infrastructures. The electrical current passing through a patient should never be so large as to cause any harm or sensation to a patient. Circuit isolation is normally achieved in all existing ECG designs using optical isolation, which can be bulky and expensive. In our design, patient-circuit isolation is achieved with the help of 220 k Ω resistors placed between the inputs and signal cables. The worst case current through the patient is less than 14 μA , which is far below the threshold causing any sensation or harm.

Furthermore, typical ECG signals are very weak (usually on the order of 1–5 mV) and can be corrupted by noise voltage which could be several times higher than the signal itself. Fortunately, most of the noisy signal is either outside the bandwidth of the ECG signal or appears in the common mode with respect to the electrodes. In order to exploit this advantage, the sensor is set to sample at a rate that is sufficiently high in terms of ECG bandwidth. An amplifier with a very high common-mode rejection ratio (CMRR) is used. As instrumentation amplifiers typically exhibit a very high CMRR, a compact, low-power, and low-noise instrumentation amplifier is used in the ECG device. This configuration features a CMRR of over 100 dB (V/V). The resistor values are large enough such that only a very small amount of average power is dissipated. Due to the same cause, little thermal noise is generated. In order to reduce common-mode noise further, a right-leg driver amplifier is used in the device to inject the common-mode

Electrocardiogram	Detect heart rate and rhythm (e.g., ischemic heart disease)
Foot pressure signal	Foot pressure monitoring health status
Blood pressure	Hypotension, emergent hypertension, and pathophysiology
Temperature	Medical diagnosis
Weight	A health factor related to diagnosis
Accelerometers	Movement pattern analysis; measures the depth of chest compressions during cardiopulmonary resuscitation
Flex	Monitoring knee movement
Galvanic skin	Skin conductance; emotional response

Table 1. Types of medical sensors.

signals back into the loop to cancel the noise. The amplification stage features a compact, low-noise, low-power signal amplifier, and a two-pole active high-pass filter. A notable characteristic feature of the output stage is that there is no low-pass filter. Digital filtering can be employed instead of analog filtering to eliminate noise above 30 Hz, allowing the device to be made even smaller at lower cost.

Another important issue is to minimize measuring error. The quantization error should be in the range of -0.36 to 0.36 mV for 100 mV, 500 mV, or 1500 mV signals. It is also critical to minimize overall power consumption. For a typical zero-offset 500 mV peak-to-baseline ECG signal, the average signal value is approximately 80 mV.

The average power consumption is negligible for a 500 mV peak-to-baseline ECG signal. The peak signal amplitude is set to 500 mV because the quantization error is very low while an insignificant amount of average power is dissipated. The input signal level is between 1 mV and 5 mV, depending on the patients, and thus a gain of 100 V/V is achieved. The tMote Sky can only measure any positive signals between 0 V and 1.5 V, so a DC offset must be added after amplification because ECG traces can exhibit significant negative deflections.

Figure 2a shows the ECG information collected from our implemented ECG healthnode. It is noted that there is very little signal distortion after digital filtering is performed, and the baseline of the signal is quite stable. The signal quality is comparable to that obtained by any existing commercial ECG device. These results demonstrate that the designed ECG healthnode can collect ECG signals with the accuracy and stability we need.

The deployment of ECG medical sensors and setup of a health monitoring system raise many challenges in medical information processing, efficient communication protocol, and information security/privacy. As shown in Fig. 3, our proposed medical sensor platform includes two major planes: a secure medical information processing plane and a cross-layer network plane. A real-time and always-on medical data monitoring system with low power consumption is desirable in this platform. An appropriate medical data

encryption scheme is adapted to the wireless network condition. A simple source data compression algorithm is utilized to reduce the amount of raw data before transmission. A fuzzy-logic-based classifier detects medical emergency events in a real-time manner to raise alerts if necessary.

The proposed architecture works on a cross-layer design, which couples several layers' functionalities jointly. The proposed cross-layer network plane provides unequal resource protection on different medical data and ensures the transmission quality of critical medical data. Unequal network resource protection of important medical data is implemented through the power scaling and rate adaptation techniques. The detailed design of each plane is discussed in the next section.

RESOURCE-AWARE SECURE INFORMATION PROCESSING

CRITICAL ECG DATA IDENTIFICATION AND TRANSMISSION

The ECG signal can be divided into the M block and the F block, with the M block containing the most important ECG information such as QRS complex, and the F block giving less important information. Both the F and M blocks are of size $2 \times QRS_{cp}$. For each block, if we define the average signal value as \bar{S} within the 2QRS window, the variance can be calculated.

In probability theory kurtosis is a measure of the *peak* of the probability distribution of a real-valued random variable. A higher kurtosis means a greater variance due to infrequent extreme deviations, as opposed to frequent modest-sized deviations. The kurtosis is expressed as γ , and the variable γ_T is defined as the kurtosis threshold. Then the proposed block classifier algorithm is designed as follows:

$$\begin{cases} B_i \in M, \gamma > \gamma_T \\ B_i \in F, \gamma > \gamma_T \end{cases} \quad (1)$$

We conduct unequal resource protection on different blocks by allocating network resources (e.g., power and data rate) to maintain reliable

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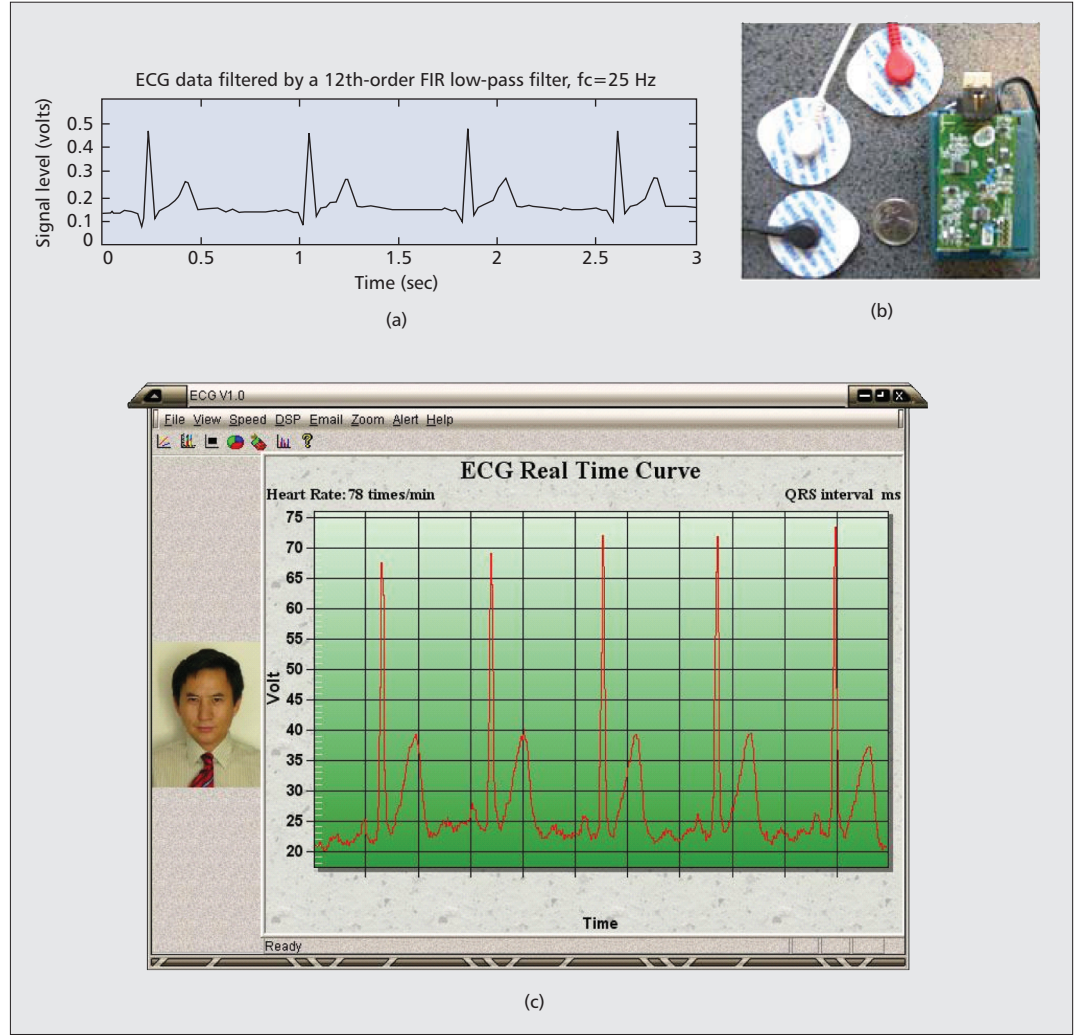


Figure 2. a) ECG data filtered by a 12th-order digital finite impulse response (FIR) low-pass filter with a cutoff frequency of 25 Hz; b) wearable wireless ECG healthnode; c) graphical user interface of ECG healthcare monitoring software.

data delivery. The optimization constraints are for the energy efficiency to be lower-bounded, or

$$\left[r_M(i), r_F(i) \right] = \underset{i=1,2,\dots,N-1}{\operatorname{argmax}} \left[E(Q) \right] \quad (2)$$

subject to $e \leq e_{\text{bound}}$, where e represents total energy consumption. $r_M(i)$ and $r_F(i)$ denote the resource allocation strategy (i.e., transmission rate, power, frame size) for the M and F blocks, respectively. λ is a weight parameter that indicates the importance level of the M block. A higher λ value means a comparatively higher importance of transmitted M blocks and a higher impact on medical data quality. The above optimization problem was derived based on our previous work [11, 12], where the average total energy consumption could be expressed as a function of desirable bit error rate (BER) requirement, frame length (L_{DATA}), control packet transmission rate (R_{CTRL}), data packet transmission rate (R_{DATA}), transmission power (P_{DATA}), and retransmission limit (RT_{max}). We can allocate these resources optimally to improve ECG signal transmission reliability. For more details of the optimization study, please refer to

[11]. $E[Q]$ is the λ -expected received packet number when resource allocation strategy $\{r_1, r_2, \dots, r_k\}$ is employed. λ is a weight parameter that indicates the importance level of the M block. A higher λ value means comparatively higher importance of transmitted M blocks and, correspondingly, a greater impact on medical data quality.

$$E[Q] = \frac{\left\{ \sum_{i=1}^{N_F} [1 - \zeta_M(i)] \right\}^{\lambda} + \sum_{i=1}^{N_M} [1 - \zeta_F(i)]}{(N_F)^{\lambda} + N_M}, \quad (3)$$

where $\zeta_F(i)$ and $\zeta_M(i)$ denote the packet error probability for the packets of the F block and M block, respectively, when network resource is allocated to protect the i th packet. λ is greater than one and is a critical parameter indicating the importance of the F block. The complexity of the proposed algorithm for critical ECG data identification and transmission optimization is $O(N^2)$ in the worst case scenario. With a limited number of input resource allocation parameters (i.e., frame length, packet transmission rate,

power, and retransmission limit) for medical signal transmission quality maximization, the proposed identification algorithm brings tolerable computational overheads in BSNs.

LOW-DELAY ADAPTIVE ENCRYPTION

Medical data such as ECG signals can be encrypted in an efficient way over wireless channels in our approach. The adaptive encryption only encrypts the major information of M blocks. The number of encrypted bits also depends on the wireless channel condition. The different kurtosis thresholds are adaptive to encrypt different parts of the ECG data. The proposed scheme encrypts data as little as possible by focusing on the most important parts of the medical information. The selective encryption approach in the proposed architecture addresses security issues for both the network controller and the wireless medical sensor node. Each wireless medical sensor samples the ECG signals. It selectively encrypts them and wirelessly transmits them to the healthnode. The proposed adaptive encryption in this architecture provides an enhanced security solution to protect data transmission over BSNs. Compared to traditional encryption approaches, it can significantly reduce computational overheads, which is suitable for the resource-limited medical sensor. As we discussed in [13], the encryption overhead is related to the number of bits to be encrypted and the unit-block encryption time, together with the encryption block size. The time delay for the encryption is proportional to the number of encrypted bits. In the proposed approach, only a portion of ECG data bits that contain major information are chosen to be encrypted. Thus, the encryption delay is significantly reduced. The principle of the proposed adaptive encryption is to only encrypt major information in M blocks rather than in all ECG blocks (both the M and F blocks), which reduces computational overheads but with the same security level as full encryption. In this approach the amount of encrypted bits is set proportional to the kurtosis γ of the M block. If γ is higher, more information from the M block would be included, and thus more bits should be encrypted. With the help of this formula, the most important information is always encrypted without increasing encryption overhead.

REAL-TIME ECG FEATURE-BASED NONLINEAR CLASSIFICATION

Many ECG classification methods have been proposed by Hu *et al.* [14] based on the training from the well-known MIT-BIH arrhythmia database. However, these algorithms are too complex for real-time ECG classification and emergency detection in a wireless BSN. In our proposed approach we extracted clinically meaningful metrics such as the QRS axis, QT-interval, ST-level, and T-wave abnormalities to conduct the classification with a supervised classification technique. We propose a Choquet-based classification scheme with a fuzzy logic measure [15, 16] to identify the significance and interaction among attributes, which also identifies the signal noise level and reports the emergency informa-

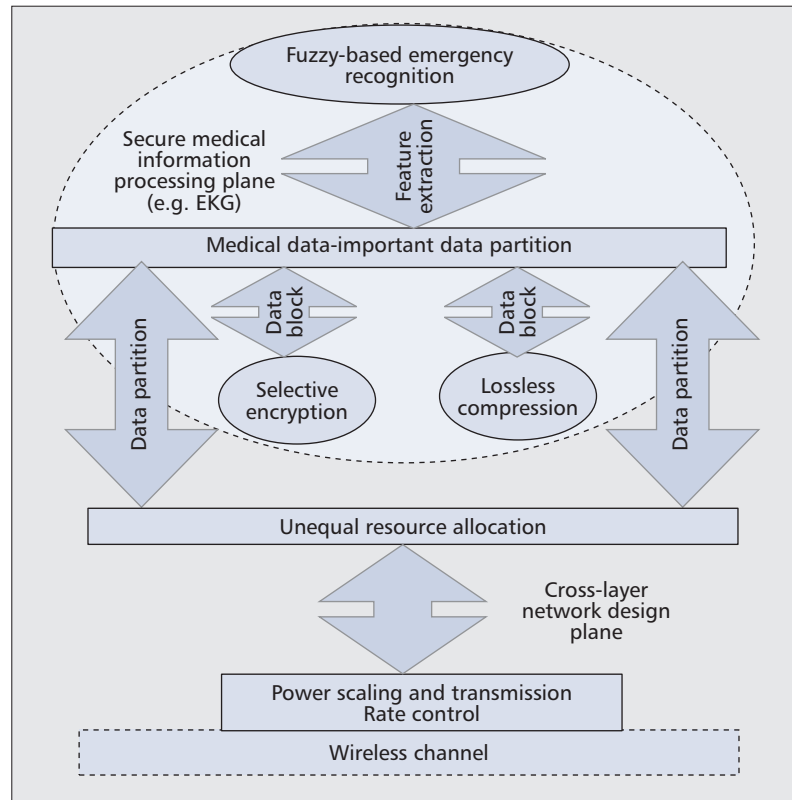


Figure 3. Secure cross-layer-based BSN platform for medical applications.

tion. The weighted Choquet integral with respect to a non-additive measure is generalized to a more comprehensive Choquet model, allowing the set function to obtain negative values and to be non-monotone. It considers the interactions among multiple clinically meaningful metrics that are likely to exist in ECG healthcare data. Compared to other typical classification methods, the Choquet-based classification approach has advantages in improving ECG data recognition performance. We use this generalized Choquet model as a projection tool to reduce the complexity of the classification problem defined in an n -dimensional space.

PERFORMANCE EVALUATION

In order to demonstrate and test the ECG device in wireless BSNs, a software system as well as a graphical user interface (GUI) utilizing C++, Java, and Nesc in TinyOS was developed as shown in Fig. 2c. The GUI is programmed in C++ and implements codes provided by the makers of Tiny OS to receive packet information in real time. The raw packet data stream is then decoded and graphed on the screen. The prototyped wearable and wireless ECG device proposed in this work, in conjunction with other technologies such as radio frequency identification (RFID) tags and patient tracking systems, will allow patients greater freedom to move about the hospital, while medical personnel can still monitor and quickly locate the patients in question.

Figure 4a shows energy consumption at different kurtosis thresholds for different QRS win-

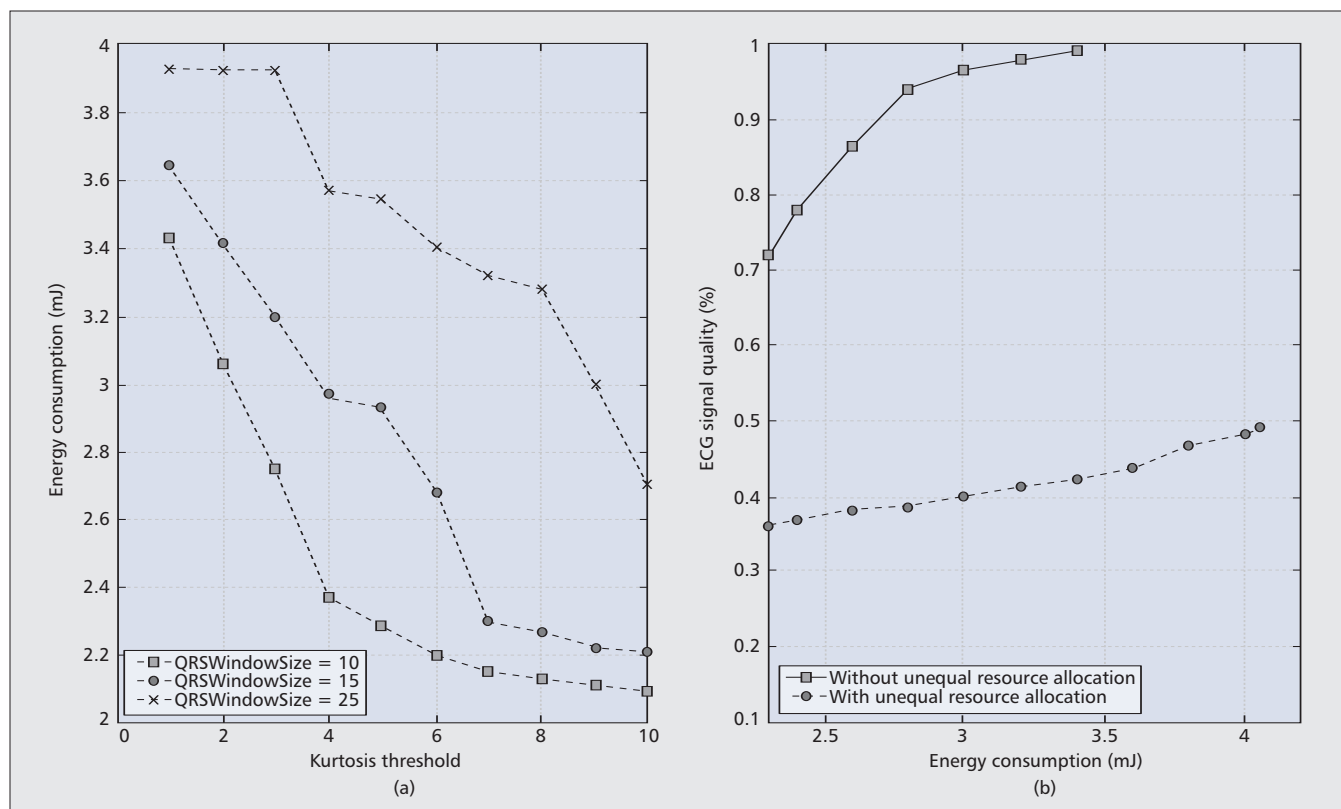


Figure 4. a) Energy consumption vs. kurtosis threshold; b) energy consumption vs. ECG signal quality.

down sizes. The increased kurtosis threshold corresponds to less protection on the packets that contain the important ECG information, and energy consumption is hence reduced. In other experiments we also found that a smaller size QRS window can lead to better ECG transmission quality. However, a smaller QRS window configuration will bring larger overheads with unnecessary protection of unimportant information that consumes more computational and energy resources. There is a trade-off between signal quality and energy consumption. Our approach proposed in the previous sections finds the strategy to achieve the best signal quality with a specified energy consumption budget. The approach allocates extra energy resources to highly protect the most important signal portion transmissions rather than all signal transmissions. The signal quality maximization problem is formed to ensure the best signal quality under the energy consumption budget as described in Eq. 3. Signal quality is measured as λ -expected received packet number. Figure 4b demonstrates the performance comparison between the proposed unequal protection approach and the traditional scheme with equal resource protections. With the same energy consumption, the proposed approach achieves an obviously better signal quality. The most important ECG part has been well protected, and energy efficiency is significantly improved.

We have also studied the security performance of the proposed selective encryption approach at different QRS window sizes. We found that the configuration with a smaller QRS window size has a shorter delay than the one

with a larger window size at different kurtosis thresholds. This means that a smaller QRS window size can truly improve real-time encryption performance, which is critical, especially when the wireless channel degrades.

CONCLUSION

In this article we proposed a BSN architecture and its corresponding algorithms for healthcare monitoring applications, especially ECG-based applications. It provides small, inexpensive, and flexible BSN solutions in contrast to existing wireless cardiac monitoring systems based on sensor networks. We have implemented a wireless ECG sensor health monitoring system and demonstrated that the proposed system is effective and practical. We also developed a secure medical information processing and communication platform in a BSN that performs unequal resource allocation, selective encryption, and intelligent emergency detection based on signal classifications, which can achieve optimized energy efficiency and signal quality with lower delay performance. The proposed platform is not only effective for the ECG healthcare applications, but can also be extended into other more general healthcare applications.

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BIOGRAPHIES

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The configuration with a smaller QRS window size has a shorter delay than the one with a larger window size at different kurtosis thresholds. This means that a smaller QRS window size can truly improve real-time encryption performance