Low-cost Fog-assisted Health-care IoT System with Energy-efficient Sensor Nodes

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***Abstract*—A better lifestyle starts with a healthy heart. Unfortunately, millions of people around the world are either directly affected by heart diseases such as coronary artery disease and heart muscle disease (Cardiomyopathy), or are indirectly having heart-related problems like heart attack and/or heart rate irregularity. Monitoring and analyzing these heart conditions in some cases could save a life if proper actions are taken accordingly. A widely used method to monitor these heart conditions is to use ECG or electrocardiography. However, devices used for ECG are costly, energy inefficient, bulky, and mostly limited to the ambulatory environment. With the advancement and higher affordability of Internet of Things (IoT), it is possible to establish better health-care by providing real-time monitoring and analysis of ECG. In this paper, we present a low-cost health monitoring system that provides continuous remote monitoring of ECG together with automatic analysis and notification. The system consists of energy-efficient sensor nodes and a fog layer altogether taking advantage of IoT. The sensor nodes collect and wirelessly transmit ECG, respiration rate, and body temperature to a smart gateway which can be accessed by appropriate care-givers. In addition, the system can represent the collected data in useful ways, perform automatic decision making and provide many advanced services such as real-time notifications for immediate attention.**

***Keywords*—** Internet-of-Things, low-cost, wearable, fog computing, health monitoring, energy-efficient, low energy.

I. Introduction

More than 422 million people in the world are related to diabetes and cardiovascular diseases which can directly or indirectly cause serious consequences such as congestive heart failure, other irregular heart rhythms, heart attack, stroke, and kidney failure [1, 2]. Delay or incorrectness in the treatment of these abnormalities can endanger a patient. Therefore, it is necessary to monitor these patients' health and notify abnormal situations to doctors in real-time. Continuous health monitoring systems can be considered as a solution for this issue. However, they are often high-cost with several limitations such as non-support advanced services including remote monitoring, or real-time notification.

Internet of Things (IoT) can be described as a convergent network infrastructure where physical and virtual objects are interconnected together [3]. With the involvement of many advanced technologies such as wireless sensor network, wireless body area network, wearable and implanted sensor, IoT shows its capabilities of solving existing problems or difficulties in health-care monitoring systems. It can help to improve the quality of service i.e. offering remote monitoring, push notification whilst reducing health-care costs.

In order to monitor patients' health, wireless sensor devices (i.e. implanted or wearable sensors) acquiring bio-signals from a human body and wirelessly sending the signals to a gateway are popularly applied. These sensor devices are small and resource constraint (i.e. limited power supply capacity). Accordingly, it is important to achieve some levels of energy efficiency in sensor devices. However, it is a challenge to reduce power consumption of sensor devices dramatically while maintaining the high quality of signals. Also, when high resolution signals are needed, it costs high power consumption for data acquisition and wireless transmission.

In conventional IoT-based systems, primary tasks of gateways are data receiving and transmitting. To improve the quality of health-care service, gateways can be upgraded by the assistance of Fog computing which can be described as a virtual platform extending the Cloud computing paradigm to the edge of the network and reducing burdens of Cloud [4–6]. For example, diversified advanced services such as edge location, low latency, geographical distribution, and mobility support can be provided with the assistance of Fog.

In order to reduce health-care costs and improve the quality of health-care service, we propose a novel low-cost remote health monitoring IoT-based system with Fog computing and energy-efficient wearable sensor devices. The wearable device, which is small and low-cost, is able to collect and wirelessly transmit the large number of high resolution signals (i.e. ECG and respiration rate) to a smart gateway. Furthermore, the wearable device's power consumption is dramatically reduced by a combination of hardware design and software-based techniques. In the system, smart gateways are integrated with the Fog layer providing a large number of advanced services such as data analysis and data processing at gateways, decision making, notifications and local data storage. Real-time decision making is regularly carried out for checking abnormal situations. When abnormality such as too low or high heart rate is detected, it sends real-time notifications to the patient and his/her doctor. Accordingly, the early stage of deterioration can be timely detected. Last but not least, doctors can remotely monitor patients' health represented in text and graphical forms in real-time via an end-terminal i.e. a smart-phone or a computer's browser. To summarize, the key contributions of this work are as follows:

- A design of energy-efficient, low-cost and wearable sensor device for collecting and wirelessly transmitting ECG, respiration rate, humidity, body temperature and room temperature
- A complete remote health monitoring system based on IoT and customized ultra low power 2.4GHz radio frequency protocol (nRF)
- Fog services for representing bio-signals in graphical waveforms, performing decision making, categorization, real-time notifications, and channel managing

This paper is organized as follows. Section II discusses related works and motivations. Section III describes the system architecture in details. Section IV presents a design of a low-cost and energy-efficient wearable sensor device. Section V presents the system's gateway architecture and a back-end system. Section VI shows an implementation of the entire health monitoring system. Section VII shows the experimental results. Section VIII concludes the work.

II. Related Work and Motivation

There have been a lot of efforts in developing remote health monitoring IoT-based systems. Gia et al. [7] propose a continuous health monitoring system based on customized 6LoWPAN. The system enables remote and real-time ECG monitoring via a reliable network.

Jiang et al. [8] propose an IoT-based system for remote facial expression monitoring. The system's sensor nodes acquire Electromyography (EMG) and transmit the data to a gateway via Wi-Fi. The bio-signals are processed and classified in Cloud with the assistance of LabVIEW.

Gomez et al. [9] introduce a patient monitoring system based on IoT for monitoring health status and recommending workouts to patients with chronic diseases. The system acquires not only bio-signals (i.e. ECG) but also contextual data (i.e. time and location). Doctor and patient can access collected data via an Android app.

Nemati et al. [10] propose a wireless wearable ECG sensor for long-term applications. The small-size sensor node can be conveniently deployed in T-shirt or undergarment for collecting and transmitting ECG data wirelessly via an ANT protocol. A patient carrying the sensor can perform his or her daily activities without any disturbance.

Fanucci et al. [11] present an integrated information and communication technology system for monitoring patients at home. The system collects ECG, SpO2, blood pressure, and a patient's weight via biomedical sensors. The collected data is transmitted to the hospital information system for remote monitoring. The system helps to reduce the number of subsequence hospitalization via its capability of supporting early detection of the alterations in vital signs.

In [12], authors present a smart health-care system using Internet of Things. The system is able to monitor different signals such as glucose level, ECG, blood pressure, body temperature, SpO2 and transmit the collected data wirelessly to Raspberry Pie via Zigbee. End-users such as doctors and care-givers can monitor the data via a mobile application.

Other systems based on Bluetooth Low Energy and IoT [13, 14] are capable of acquiring and transmitting ECG wirelessly with low power consumption. By applying these systems at home and hospital, doctors can monitor ECG and heart rate of patients in real-time.

Although these systems can improve the quality of health-care service via their advancement (i.e. remote and real-time monitoring), they still have limitations such as high power consumption of sensor nodes or lack of necessary services (i.e. push notification, and local storage). Some systems based on Wi-Fi and Bluetooth are not energy-efficient because these protocols consume high power. Although other systems pay attention to reducing transmission power consumption of sensor nodes by using low power wireless transmission protocols (i.e. ANT, 6LoWPAN, and BLE), sensor nodes are still not energy-efficient due to high power consumption of other components (i.e. memory, micro-controller, and voltage regulator). By applying a comprehensive combination of software and hardware design methods altogether with a customized low-power wireless transmission protocol, power consumption of sensor nodes can be considerably reduced. In most of the systems, the quality of health-care service cannot be considered as comprehensive since the number of advanced services is limited.

This paper aims to provide an enhanced real-time and remote health monitoring IoT system. The major difference of this system from previous works is the adoption of energy-efficient sensor nodes based on the customized nRF protocol. The sensor nodes are carefully designed in terms of both software and hardware for reducing power consumption as much as possible. In addition, the system overcomes previously mentioned limitations in other systems. With the assistance of Fog computing in smart gateways, the quality of health-care service is dramatically improved.

III. Health monitoring IoT-based system architecture

The proposed health monitoring IoT-based system, whose architecture is shown in Fig. 1, is comprised of sensor nodes, gateways, and a back-end system. The sensor node acquires bio-signals (i.e. ECG, respiration, human temperature) and contextual data (i.e. room humidity and temperature). Then, it transmits the collected data to a gateway via an nRF module which is low-power, low-cost (about 1 Euro) and has fully customizable parameters. A selection of low transmission data rate is preferred for reducing energy consumption of the sensor node. Depending on particular signals and usages, signals can be kept intact or preprocessed before transmitting. The gateway in the system receives incoming data from the sensor nodes and transmits the data to Cloud. Similarly, data can be raw or processed data. In addition, the gateway with Fog can provide the large number of advanced services shown in Fig. 3 for improving the quality of health-care service.

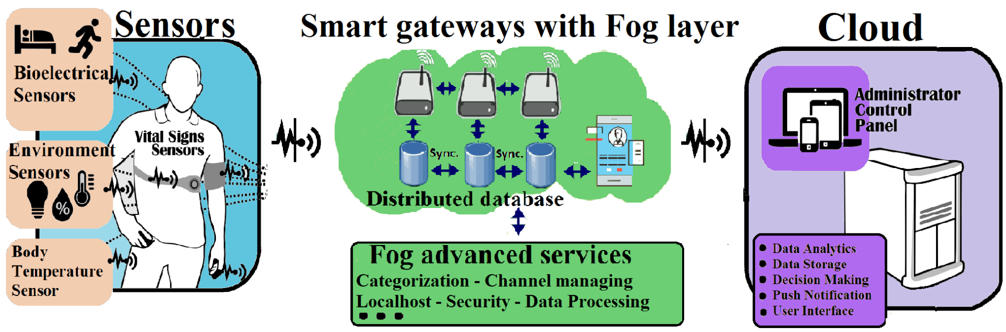

Fig. 1. A IoT-based e-health monitoring system architecture

A back-end system consisting of Cloud and an end-user application performs several tasks such as storage, data analysis and graphing, and push notification. End-users (e.g. doctors) can monitor their patients remotely by accessing real-time and history data in Cloud via an Internet browser or a mobile app.

IV. Sensor Node Design

A sensor node in the system primarily consists of a micro-controller, an nRF block, and specified sensors which are connected via SPI or I2C. The SPI protocol is preferred in the design due to its benefits of high data rate support and low energy consumption [15]. However, the more components are connected via SPI, the more difficult the issues get in terms of data categorization and verification. If the issues cannot be appropriately handled, the quality of data reduces.

Obviously, surrounding temperature, humidity, and body temperature do not change rapidly in seconds. Therefore, these can be acquired with a low data rate (i.e. 1 sample/s or 1 sample/30s). According to [16], a slight difference of 15 μJ energy consumption is observed when communicating with low data rate via SPI and I2C. Hence, I2C is used for connecting temperature and humidity sensors to the micro-controller while SPI is applied for connecting other components. The architecture of the sensor node is shown in Fig. 2.

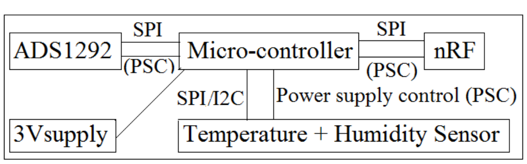

Fig. 2. Architecture of Sensor Node

Sensors including bio-potential and contextual measurement sensors must fulfill the requirement of low energy consumption. In addition, sensors must be capable of fast response and data sampling with low-noise, high precision and accurateness.

A micro-controller plays the most important role in the sensor node. It acquires data from sensors and transmits the data to the nRF block via SPI. In addition, it controls power supply of sensors and the nRF block. Therefore, a high performance and ultra-low-power micro-controller with power management modes such as several sleep modes is suitable for the sensor node.

an nRF module consisting of an nRF integrated circuit (IC) and an on-PCB printed antenna is chosen for the design because it consumes low energy while supporting high data rates and communication bandwidth. In addition, it can be fully customized for the system. For example, it supports on-air data rate up to 2Mbps but 250kbps can be selected for reducing power consumption.

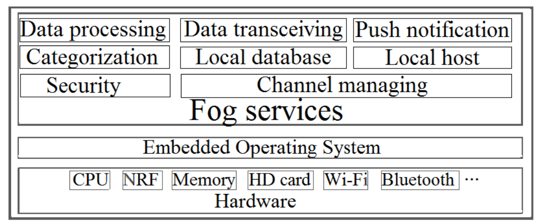

Fig. 3. Gateway structure

V. Gateway Structure

A gateway is supplied by a wall power outlet and fixed at a single room (i.e. a hospital room). The gateway integrated with Fog services shown in Fig. 3 is designed for serving several sensor nodes (i.e. 5-10 nodes). Detailed information of these services are explained as follows:

A. Data transceiving

To receive data via an nRF, the gateway is equipped with an nRF transceiver component. The component includes a micro-controller and an nRF module which are similar to the ones used in the sensor node. All collected data from the nRF transceiver is transmitted via UART to the gateway's primary MCU for further processing because the gateway's MCU is more powerful. The processed data is sent to Cloud via Ethernet or Wi-Fi. Accordingly, real-time data can be stored and monitored at Cloud servers.

B. Data processing

Processing of bio-signals includes pre-processing to eliminate noise from signals and extract useful features for further interpretation. Data processing service in the system is similar to ECG feature extraction presented in [17]. Data processing helps to improve the quality of health-care service and save transmission bandwidth between gateways and Cloud.

C. Local database

Local database includes two distinct databases which are internal and external usage databases. Internal usage database stores intact information which is only edited or updated by system administrators. For example, reference data (i.e. reference tables) used in algorithms or services (i.e. data processing and push notification) is stored in this database. The internal database is not synchronized with Cloud in most of the cases except a case of back-up data. In this case, data is encoded before being sending to Cloud. These specifications of the internal usage database help to avoid some unexpected security attacks from outsiders. Oppositely, the external usage database stores bio-medical signals and contextual data which are real-time synchronized with Cloud servers. Due to a limited storage capacity, the data is stored in the database for a period of time (i.e. several hours or a day), then replaced by new-coming data. Accordingly, the real-time data can be accessed at the Fog layer or at Cloud. For monitoring data in history, Cloud must be accessed.

D. Security

In order to protect information and resources of the system from unauthorized accesses, security and cryptography methods are applied in the Fog layer. It is a challenging task because the methods must not cause a dramatic increase in the system's latency.

E. Localhost with user interface

In order to provide real-time health monitoring at the gateway, localhost with user interface is integrated into the Fog layer. Concisely, a web server is run at the gateway for hosting a web-page which is user-friendly and able to represent both raw and processed data in text and graphical forms. The web-page provides functions such as a log-in form with a username and a password, or a searching tool.

F. Categorization service

In the Fog layer, a mechanism for classifying connected devices is integrated. The system regularly performs the mechanism for categorizing local and external connected devices. For local connected devices, real-time monitored data is directly retrieved from the Fog layer's local database instead of Cloud. This mechanism helps to reduce latency of the monitored data because the data transmission's path is shorter. When devices do not connect to the local network, data monitored at an end-user' s terminal (i.e. an Internet browser, or a mobile application) is retrieved from Cloud.

G. Push notification

Push notification is used for notifying end-users in case of abnormality. For example, when body temperature of a patient is too high over a threshold value, the push notification is triggered to send real-time messages to the patient and a doctor responsible for the patient.

H. Channel managing

It is important to provide a channel managing service in the Fog layer because it helps to avoid channel conflicting which causes incorrect data at a gateway's receiver. The service manages 126 channels of an nRF protocol to guarantee that each specific channel is reserved for a sensor node or a group of sensor nodes in which a channel with a higher frequency (channel with a higher number) will be given first. There is a table for recording assigned and unassigned channels. Unassigned channels will be verified for availability before being assigned for a device. The main purpose is to avoid channel conflicting between nRF channels. In the future work, channel conflicting between nRF and other technologies based on 2.4 GHz such as Wi-Fi will be investigated. Some channels (i.e. channel 116-126) are reserved for emergency notification and future usage. The channel managing service verifies incoming data regularly. When it detects some abnormality at a specific channel, it sends a request message to the channel and waits for an acknowledgement message(s) from a sensor node or a group of sensor nodes. By analyzing and investigating the acknowledgement message(s), it can detect channel conflicting. In case of a conflict, a push notification is triggered to notify the problem to system administrators.

VI. Implementation

The implementation of the system is divided into two parts described in detailed as follows:

A. Node implementation

ADS1292 is a low-cost (about 11 Euros), low-noise, and low-power analog front-end device for acquiring multichannel ECG with high data rates (i.e. 1000 samples/s). In the implementation, 2 ECG channels with a data rate of 250 samples/s are used. According to [18], the high quality of ECG signals can be obtained when sampling at 250 samples/s and higher data rates.

For acquiring humidity, environmental and body temperature, two BME280 sensors are used. These sensors are low-cost (5 Euros for each) and low-power while they provide high precision data and accurate measurements.

A low cost (1 Euro) and ultra-low power AVR ATMEGA328P micro-controller is used in the sensor node. It can support up to 20 MHz but power consumption is high. To reduce power consumption, 8 MHz is applied. As mentioned, the micro-controller controls voltage supply of sensors and an nRF block. Therefore, voltage supply must be appropriately chosen. In our implementation, 3V is the best voltage supply as suiting to all components. When the voltage supply is slightly less than 3V (i.e. 2.7V) due to a voltage drop characteristic of a battery, the sensor node is able to operate appropriately.

an nRF24L01 transceiver is used in the sensor node because of its low power consumption and low cost. As mentioned, it is customized for sending and receiving data with a data rate of 250kbps for reducing power consumption.

In order to protect data transmitted over an nRF network, AES-256 [19], which is a block cipher utilizing a 256-bit symmetric key for encryption and decryption, is implemented in the sensor node. The AES-256 is used because the algorithm is strong and the sensor node can perform the encryption algorithm fast. However, applying the algorithm increases power consumption of the sensor node and latency of the system. Results are shown in Section VII.

B. Gateway and back-end system implementation

In our implementation, Orange Pi One (about 14 Euros) is used as a core of the gateway for providing all mentioned services. Orange Pi One consists of Quad-core Cortex-A7 at 600 MHz each, 512MB low power memory, high speed and high capacity SD card (64GB), and several types of connectivity including Ethernet. As mentioned, in order to provide a capability of nRF wireless communication, the nRF component is added to Orange Pi via a UART port. The nRF component in the gateway including nRFL2401 [20] and AT-Mega328P [21] is similar to the nRF component in the sensor node. In order to receive data from the nRF component, a Python application is constructed in Orange Pi One. The application reads available data from the UART port then stores the data into the synchronized database. Simultaneously, the application transmits the collected data to Cloud.

Data processing is implemented in the Fog layer via several filtering and advanced processing algorithms. For example, moving average filter is first applied on raw ECG signal to remove baseline wander. Then 50 Hz notch Butterworth filter is applied to eliminate powerline interference. Finally, R peaks in ECG waveform are detected with conditional peak detection and R to R intervals are calculated for further application specific feature extraction. All of the data processing algorithms are implemented in Python.

Local database including both reference and synchronized database is implemented with the assistance of MySQL and a local SD card. For example, bio-signals and contextual data altogether with the recorded time are stored in the MySQL database. In addition, the MySQL database stores usernames and passwords of all users.

IPtables [22] and AES-256 used at Fog are implemented in C. IPtables is tables containing chains of rules for the treatment of incoming and outgoing packets at a gateway.

For implementing the web-page and server in the Fog layer, several up-to-date technologies such as HTML5, CSS, JavaScript, JSON, Python, and XML are used. The web-page is user-friendly and it is able to represent real-time data in text and graphical forms.

A channel managing service is implemented at Fog in C and Python. C is mainly used at an nRF receiving part while Python is used at Orange Pi One.

Categorization is implemented by a combination of a scanning service and database. By customizing an ”iw” package provided in Linux kernel, information of all devices connecting to a specific gateway via Wi-Fi can be acquired without any effort. The ”iw” package based on CLI configuration utility supports all new drivers of wireless devices. Although the ”iw” package has been in a further development process, it is suitable for the categorization service. The acquired information of connected wireless devices is recorded in tables in the database. The scanning service triggers an ”iw” command to update the information of connected devices regularly. The latency of running the ”iw” package regularly is not high because each gateway only serves several connected devices in a single room.

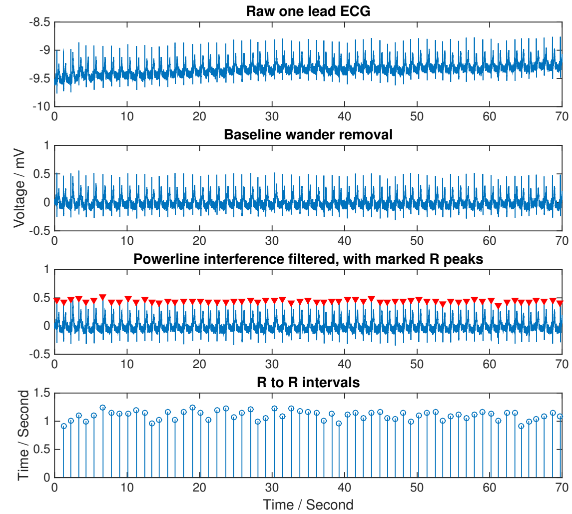

Fig. 4. Signal processing with one lead ECG

Push notification is implemented in both the fog layer and Cloud. When an end-user such as a doctor currently connects a local network (i.e. the same network with gateway’s network), the push notification service at the Fog layer is triggered for sending notification messages to the end-user directly via a TCP server installed in the gateway. When an end-user does not connect to a local network, the push notification service in Cloud implemented by a Google push service API is triggered for sending real-time notification messages.

VII. Experimental results

Results of ECG signal processing at the system’s gateway is presented in Fig. 4. It depicts the ECG data presented at Fog’s interface in graphical waveforms. The data includes raw data and processed data i.e. R-R intervals for calculating the heart rate.The ECG is acquired with one channel from a healthy person at a sample rate of 1000 samples/s, where the two electrodes are placed on the left wrist and the right wrist, respectively. Although the sensor node is designed for acquiring ECG with a data rate of 250 samples/s, a data rate of 1000 samples/s is applied in the experiment for testing the sensor node’s capability of sampling and transmitting with higher data rates. Results show that the quality of signals is still high when acquiring and transmitting at 1000 samples/s.

In order to measure power consumption of a sensor node, the developed prototype is tested while in operation. Results shown in Table I indicate that average current of the sensor node is very low about 6.5 mA for gathering and transmitting all data including ECG, body temperature, environment temperature, and humidity. In case of applying AES-256, average current of the node increases up to 7.01 mA.

The developed prototype of the sensor node shown in Fig. 5 approves its small physical size beside a two Euro coin for comparison. The actual size of the sensor node can be reduced dramatically since the prototype has extra many components for debugging purposes. The device and its battery are lightweight. With a 1000 mAh lithium button cell, the sensor node

TABLE I
AVERAGE POWER CONSUMPTION OF THE HEALTH MONITORING DEVICE AT A DATA RATE OF 18 KBPS

Mode	Voltage (V)	Average power (mW)
Idle	3	1.2
Active without AES-256	3	19.5
Active with AES-256	3	21.03

TABLE II
LATENCY OF RUNNING AES-256 FOR ENCRYPTING AND DECRYPTING 16 BYTES DATA AT SENSOR NODES AND GATEWAYS

Device	Algorithm (V)	Latency (μs)
sensor node	AES-256 encryption	170
Gateway	AES-256 decryption	38
Gateway	AES-256 encryption	42
Cloud server	AES-256 decryption	8

can operate up to 155 hours. Furthermore, the cost of the sensor node and the gateway is low, around 26 Euros and 20 Euros, respectively. Hence, the sensor node can be as a wearable device.

For testing the quality of data during transmission, two types of data including fixed data and actual data collected from sensors are used during experiments. Results show that data loss does not occur during communicating and longer range transmission requires higher power.

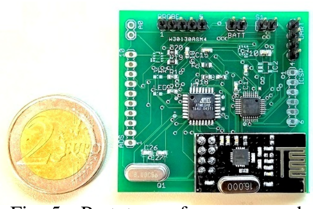

Fig. 5. Prototype of a sensor node

Table II shows that, when using AES-256 in a sensor node, average latency of the sensor node and the system increases about 170 μs and 260 μs, respectively. However, these small increases do not cause dramatically negative impacts on the system's performance and latency.

VIII. CONCLUSIONS

In this paper, a low-cost remote health monitoring IoT-based system with the Fog layer has been proposed. The designed system is able to acquire data including bio-signals (i.e. ECG and respiration) and contextual data (i.e. environment temperature and humidity) and transmit the data wirelessly for real-time and remote monitoring. In addition, with the assistance of the Fog layer, the system provides advanced services such as data processing, categorization, push notification and channel management for improving the quality of health-care service. Furthermore, a design of a low-cost and portable sensor node has been presented. The sensor node is able to operate for a long period of time reaching up to 155 hours due to its high energy efficiency. By applying this system at hospitals and homes, emergencies (i.e. related to cardiovascular diseases) can be notified in real-time to medical doctors for in time action to avoid serious consequences.

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