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Low-Power Wireless Wearable ECG Monitoring System Based on BMD101

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Abstract: Cardiovascular disease (CVD) threats people's health heavily and long-term electrocardiogram (ECG) monitoring is of great meaning for better treatment. To realize the remote long-term ECG monitoring, a low-power wireless wearable ECG monitoring system is proposed in this paper.The wearable telemetry ECG monitoring system includes three parts, respectively, ECG monitoring device, mobile phone, and the cloud server. The ECG monitoring device, abbreviated as ECGM, is designed based on BMD101 sensor chip and CC2640R2F wireless MCU. The ECGM collects ECG signals from the fabric electrodes adhered to users' chest, preprocesses the signal to eliminate the injected noise, and then sends the digital output data to users' hand-held mobile phones through Bluetooth low energy (BLE). The phones are in charge of ECG classification and uploading both original and processed ECG data to the cloud server. The cloud server stores users' ECG data, accounts for huge calculation in ECG processing & diagnosing, and provides telemetry monitoring service for cardiologists. Users, namely patients, view ECG on their phones and acquire treatment advices from both machine and cardiologists. The novelty of the system lie in the combination of low-power ECG sensor chip and BLE chip, and thereby it features ultra-low power consumption and high signal quality.

Key Words: ECG, Wearable device, Telemetry monitoring, BMD101

1 Introduction

In 2015, cardiovascular disease (CVD) caused about 17.7 million deaths worldwide, accounting for 31.5% of the overall total of 56 million deaths and the cardiovascular mortality rates in low- and middle-income countries is much higher than that in high-income countries [1]. Thus CVD threats people's health heavily and patients' full-day electrocardiogram (ECG) signals are badly needed for treatment. However, it is infeasible for CVD patients to lie in the hospital for 24-hour ECG monitoring. Therefore wearable remote ECG monitoring device is of great significance in both assisting doctor to treat CVD patients and helping patients' family care for patients better.

Wearable monitoring device bring some new problem while it gets more and more popular among consumers. One is that the collected ECG signals, which output as electrode voltage generally ranging from 0.1 mV to 2.5 mV [2], are easy to be disturbed by noise and how to eliminate the signal noise is the first problem to design a wearable ECG monitoring device. The technique to filter the noise in ECG signals can be summed up as two ways: hardware filtering and software filtering. Compared to hardware filtering, Software filtering shows several apparent advantages, such as low cost, low circuit complexity, high accuracy, and high flexibility. There are four main types of noise in ECG acquisition, namely low-frequency baseline drift, power frequency interference, muscles movement interference, contact interference [2], and the efforts put into finding out excellent algorithm to reduce the damage brought by these noise sources are particularly important when design a ECG monitoring device.

Another problem that can't be ignored is the battery life of the designed ECG device. With no great technique breakthrough in battery energy storage density, an ultra-low energy consumption feature is crucial for a qualified wearable ECG monitoring device because users hope the device keep working for a relatively long time, e.g. a week. The major source of power consumption in a wearable ECG monitoring device is the wireless transceiver [3]. On the basis of using ultra-low power components as far as possible, therefore, minimizing the use of transceiver and compressing data flow can effectively reduce the overall power consumption of the device. Recent years, in addition to filtering and lowering power consumption, the encryption of ECG signal has gradually attracted the attention of the researchers. Once patients' ECG signals were stolen by someone with ulterior motives during transmission, patients may get into some unexpected trouble.

Fensli et al.[4] developed a prototype of wireless ECG monitoring system making no-lead-wire monitoring come true by transmitting the signal gained from electrodes to handheld devices wirelessly. Yoo et al.[5] integrated wireless network system into the breast band using planar-fashionable circuit board (P-FCB). In addition, on the basis of body sensor networks (BSN), a dry P-FCB electrode and signal acquisition circuit were integrated to realize wireless real-time ECG monitoring. Teo et al.[6] designed wireless sensor nodes based on the low-power system on chip (SoC), providing continuous and real-time ECG monitoring service cooperating with conventional electrodes, and presented a suitable solution for wearable wireless sensor nodes. Lee et al.[7] proposed a bio-signal acquisition and classification system with wireless telemetry for BSN. The system, which contains three chips, namely, a body-end chip, a receiving-end chip, and a classification chip, can correctly diagnose heart disease based on the MIT-BIH arrhythmia database and assist the cardiologists in diagnosing their patients. Deepu et al.[3] presented a design of a low-power 3-lead ECG-on-chip with integrated real-time QRS detection and lossless

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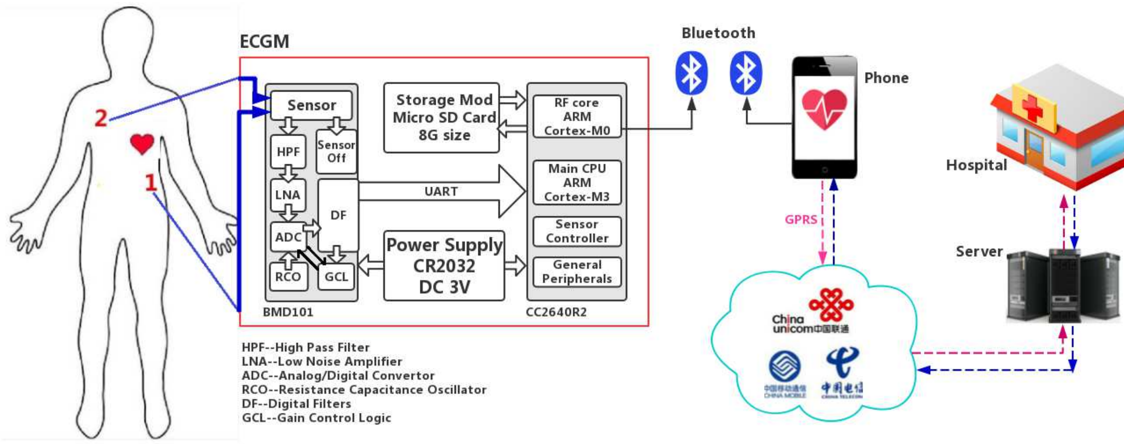

Fig. 1: ECG telemetry monitoring system.

data compression for wearable wireless ECG sensors. Satija et al.[8] implemented IoT-enabled real-time ECG monitoring framework using ECG sensors, Arduino, android phone, Bluetooth, and cloud server. Novelly, a light-weight ECG signal quality-aware (SQA) method was employed to classify the acquired signal into acceptable or unacceptable class.

This paper proposes a new solution for wearable ECG monitoring which features ultra-low power consumption and high signal quality. The wearable telemetry ECG monitoring system includes three parts, namely, ECG monitoring device (ECGM), mobile phone, cloud server. ECGM collect ECG signals through electrodes adhered to skin, preprocess the original signals to eliminate the noise, and then ECGM send the preprocessed signals wirelessly to mobile phone through Bluetooth Low Energy (BLE). The signals are processed for feature extraction and ECG signal classification using high-performance mobile phone and then uploaded to the cloud server when WiFi or GPRS is available for users. Cardiologists can monitor patients' ECG requested from the server for diagnosis and the server can also automatically diagnose patients' symptom by matching the uploaded signals with the standard signals from MIT-BIH arrhythmia database. Of course, users, usually CVD patients, can check their ECG on their phone and receive the diagnosis results and suitable instructions from both cardiologists and the cloud server's automatic diagnosis.

The key in the proposed system lies in the design of ECGM. The ECGM should mainly contain the following parts: ECG acquisition circuit, BLE circuit, additional hardware including power circuit, electrodes, etc. In order to lower the overall power consumption, integration circuit should be used as much as possible to simplify the circuit complexity. The ECG acquisition circuit is realized on the basis of BMD101 chip from NeuroSky, a company focusing on bio-sensing technology, which features small size and low power consumption. As for the BLE circuit, CC2640R2FF, a wireless microcontroller unit (MCU) fabricated by Texas Instrument (TI), is used to connect the ECGM with users' phone and transmit ECG signals wirelessly. The power of the ECGM is supplied by a rechargeable button-cell battery and in this paper a rechargeable CR2032 is responsible for the power supply of ECGM. To ensure a long-time continuous ECG monitoring, suitable electrodes are unignorable as well in the whole device, thus two fabric electrodes instead of conventional Ag/AgCl electrodes are going to be adhered to skin for continuous monitoring. By the way, to prevent the wireless connection from being discontinued, a large enough micro SD card is applied to a storage module which is necessary for data retransmission after a disconnection occurs.

This paper is organized as follows. Section 2 describes the proposed system and the main hardware. Section 3 introduces digital packet parsing, Bluetooth LE, and the framework of communication program briefly. Section 4 concludes the paper and points out the future research direction..

2 Wearable ECG Telemetry Monitoring System

The proposed system is shown in Fig. 1. The ECG signals are sensed by the BMD101 circuit and converted to digital signals. The data are then sent out by CC2640R2F circuit. Users' phones receive the signals through BLE and do digital signal processing (DSP). The system can be divided into three main parts, namely, the body-end circuit named ECGM, the receiving-end circuit implemented by an existing mobile phone, and the cloud server. The design objectives of the ECGM, which are composed of the BMD101 circuit and the CC2640R2F circuit mainly, are low enough power consumption and high enough acquisition resolution. To lower the power consumption, the ECGM should have low circuit complexity and require a low-power wireless transmission module. At the same time, a high resolution ADC is needed to achieve the demand of high acquisition resolution. For the receiving-end circuit, to simplify the system complexity and reduce users' difficulty in use, this paper utilizes users' phones as the digital signal receiver and processor. The task in the receiving-end circuit namely phone is only programming for recovering the ratio frequency signal and classifying the ECG signal. That means the hardware design of the proposed system is the implementation of the ECGM. The following sections describe the main concerns of the proposed ECGM.

2.1 BMD101 Circuit

The BMD101 circuit works as a bio-signal processor in this system. BMD101 is the 3rd generation bio-signal system-on-chip (SoC) of NeuroSky. The SoC is designed with an advanced analog front-end (AFE) circuitry and a flexible, powerful digital signal processing (DSP) structure, targeting bio-signal inputs ranging from uV to mV level.

For the AFE part, the main components are a low-noise-amplifier (LNA) and a 16-bit high resolution analog-to-digital converter (ADC). Fig. 2 illustrates the function blocks of the AFE and its interfaces to sensor and application specific intergrated circuits (ASIC) digital section. The AFE receives low amplitude differential analog input signals. To remove the large, slowly varying DC components in collected signal, a high pass filter (HPF) is fully integrated. Then the signal is amplified by the programmable-gain LNA and the output of LNA is converted to a digital bit stream by the 16-bit ADC. BMD101 has built-in sensor-off detection capability. Any resistance between two sensor input pins that exceeds typically 19 25 Meg Ohms will trigger the sensor-off status. Also, the BMD101 contains an internal low drop out (LDO) which consists of a bandgap cell to generate a 1.2v reference followed by two separate unity gain buffers, for the analog and digital supplies. A digitally controlled oscillator (DCO) is included in the BMD101 as well, which provides a fully integrated 22.1MHz clock reference signal. The majority of the filtering of the bio-signal in this system will be done in the digital domain. It is expected that the main interference is due to pick-up of the local power-supply frequency, i.e. 50Hz or 60Hz, depending on the geographical region. The BMD101 has low DC offset levels as referred to the input of the ASIC, very low input referred noise and a low noise floor. It has good signal-to-noise ratio (SNR) and very good ENOB for the ECG application ranges. BMD101 common mode rejection ratio (CMRR) levels are also very low.

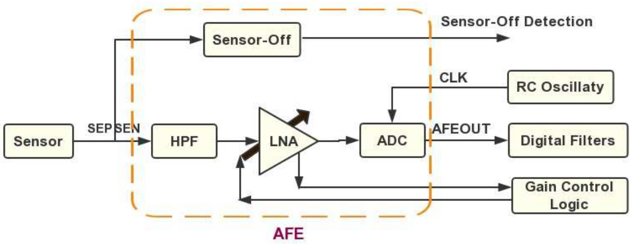

Fig. 2: Block diagram of AFE. [10]

The heart of the BMD101 is a powerful system management unit and the unit is in charge of overall system configuration, operation management, internal/external communication, proprietary algorithm computation, and power management. Under the supervision of the system management unit, the BMD101 also comes with a hardwired DSP block to accelerate calculations. Fig. 3 shows the digital signal processing data path.

After data leaves the ADC, it goes through the digital filters. The first filter is a configurable notch filter which is typically customized to be a 50Hz or 60Hz or both notch through configuration. The notch rejection is usually -63dB for both 50Hz and 60Hz. The noise lead by power frequency interference can be eliminated by the notch filter. Then the data is processed by a low-pass filter (LPF), which owns 100Hz cutoff frequency. The LPF provides a stable pass-band to the cutoff frequency and -40dB at the stop frequency. Usually the frequency of the noise caused by muscles movement interference ranges from 10Hz to 2kHz and the noise is mainly distributed in the high frequency part. Thus, the LPF can effectively reduce the muscles movement interference. Finally, the row data with CRC checksum is sent out through universal asynchronous receiver/transmitter (UART).

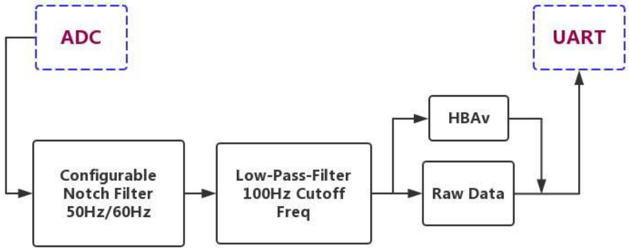

Fig. 3: Digital signal processing data path. [10]

2.2 CC2640R2F Circuit

To transmit the data from BMD101, a wireless transmission technique is required. Nowadays there are several popular wireless technique in internet of things (IoT), namely, WiFi, Bluetooth LE, GPRS, ZigBee, FSK, etc. Considering uses need ECG monitoring at home instead of hospital, ZigBee network is not a feasible solution. WiFi brings relatively high power consumption for mobile phone and ECGM, while GPRS brings additional communication cost. On the whole, Bluetooth low energy (BLE) seems the best choice for personal ECG monitoring at home.

CC2640R2F is a bluetooth ultra-low energy wireless MCU with a main CPU, a radio frequency (RF) core, a sensor controller and other general peripherals/modules. The chip is designed mainly for Bluetooth 4.2 or Bluetooth 5 low-energy application. The device is a member of the SimpleLink ultra-low power CC26xx family of cost-effective, 2.4-GHz RF devices. Very low active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin cell batteries and in energy-harvesting applications. An illustration of function framework of CC2640R2F is presented in Fig. 4.

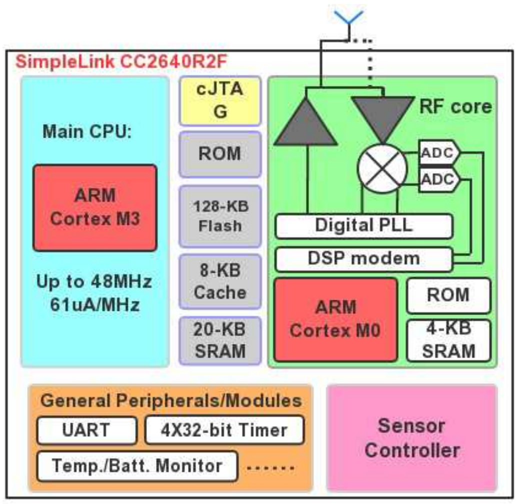

Fig. 4: Function framework of CC2640R2F. [11]

The SimpleLink CC2640R2F Wireless MCU contains an ARM Cortex-M3 (CM3) 32-bit CPU, which runs the application and the higher layers of the protocol stack. The CM3 processor provides a high-performance, low-cost platform that meets the system requirements of minimal memory implementation, and low-power consumption, while delivering outstanding computational performance and exceptional system response to interrupts.

The RF Core contains an ARM Cortex-M0 processor that interfaces the analog RF and base-band circuitries, handles data to and from the system side, and assembles the information bits in a given packet structure. The RF core offers a high level, command-based API to the main CPU. The RF core is capable of autonomously handling the time-critical aspects of the radio protocols (Bluetooth low energy) thus offloading the main CPU and leaving more resources for the user application. The RF core has a dedicated 4-KB SRAM block and runs initially from separate ROM memory. The ARM Cortex-M0 processor is not programmable by customers.

The Sensor Controller contains circuitry that can be selectively enabled in standby mode. The peripherals in this domain may be controlled by the Sensor Controller Engine, which is a proprietary power-optimized CPU. This CPU can read and monitor sensors or perform other tasks autonomously, thereby significantly reducing power consumption and offloading the main CM3 CPU.

2.3 Power Supply

The BMD101 chip requires 3.3V (+/-10%) DC power supply and the CC2640R2F needs DC power voltage ranging from 1.8V to 3.8V. Taking other discrete components into account, a 3V battery is a nice choice in ECGM. To reduce the volume of ECGM as much as possible, a rechargeable CR2032 is applied. CR2032 is one type of button-cell battery with rated voltage 3V and capacity of about 180 mAh. Rechargeable feature makes it more convenient for users because they don't have to buy a new battery from supermarket. What is worth noting is, the voltage will decrease continuously as the battery is used, proper voltage stabilizing circuit is necessary. A TPS63001 booster chip from TI is a not bad solution for power conversion. The chip features small volume, low cost, low power consumption, high conversion efficiency, wide input voltage, etc.

2.4 Electrodes

For BMD101, there are some limits in selection of electrodes. Electrodes suitable for ECG acquisition using BMD101 should be stainless steel, silver-silver chloride (Ag-AgCl), conductive cloth, etc. The comparison of these types of electrode is shown in Table. 1.The traditional Ag/AgCl electrodes are irritating for long-term use, while Stiff material dry electrodes cause a bad experience for users [9]. Though non-contact dry electrodes which based on capacitive coupling is very comfortable for wearing, how to inhibit motion artifacts is still a big problem. To ensure long-time monitoring and users' comfort, thereby, fabric electrodes are used in this design. As for dimensions of sensors, an about 10mm-diameter electrode is recommended.

3 Software Implementation

The software part in the whole ECG monitoring system consists of sensor-end, BLE-end, phone-end, and server-end. The program in sensor-end lies in BMD101 core. It controls the sensor chip to collect ECG signals, preprocess the signals, and convert them into digital out packet. This software part is built in the BMD101 chip and it's no need to change. What the tasks in software are designing the program for the other three ends. The BLE-end program receives the digital output packets from BMD101 and sends them to mobile phones. The phone-end program receives the data through BLE, classifies ECG signals, and communicates with the cloud server. As for the server-end program, it stores the data uploaded by users' phones, in charge of some complex calculations, and supplies remote monitoring service. Limited to the space, this paper just introduces the main parts of BLE-end program.

3.1 Digital Output Packets Parsing

To read the ECG data from BMD101, parsing the data packet is indispensable. BMD101 communicates through UART interfaces. The interface deploys a 1 start bit, 8 data bits, and 1 stop bit format. A digital output packet of the UART interface follows the scheme in Fig. 5. Packets are sent as an asynchronous serial stream of bytes. Each packet begins with its Header, followed by its Data Payload, and ends with its CRC checksum byte. The Data Payload itself consists of a continuous series of DataRows. Parsing a Data Payload involves parsing each DataRow until all the bytes of the Data Payload have been parsed. A DataRow consists of bytes which are showed in Fig. 5, too. To parse a packet, the following steps are necessary:

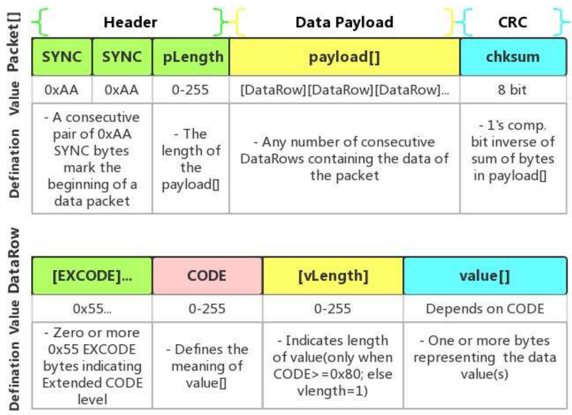

Fig. 5: Form of a packet and a DataRow. [10]

- Keep reading bytes from the stream until two continuous [SYNC] bytes are encountered.
- Read the [pLength] byte and the next [pLength] bytes of the payload[], save them and sum up each byte as it is read by incrementing a checksum accumulator.
- Take the lowest 8 bits of the checksum accumulator and invert them.
- Read the [CRC] byte and verify that it matches the calculated checksum above.

Table 1: Comparison between electrodes

Category	Representative material	Impedance	Signal quality	Signal stability	Human comfort
Conventional wet electrode	Ag/AgCl	Low	Good	Good	Bad,irritating
Stiff material dry electrode	Stainless steel	High	Medium	Bad	Relatively bad
Soft/flexible material dry electrode	Conductive foam	High	Medium	Bad	Medium
Fabric dry electrode	Conductive fabric	High	Medium	Medium	Good
Non-contact dry electrode	Metal, fabric, ...	High	Bad	Bad	Good

- Loop parsing DataRows until all bytes have been parsed from the data payload[].
  - Parse the [EXCODE], [CODE], [LENGTH], respectively, and count the number of the [EXCODE].
  - Parse and handle the [Value] byte(s) of the current DataRow, based on the DataRow's [EXCODE] level, [CODE], and [LENGTH].

Only all the steps described above are executed correctly in sequence the packet can be parsed.

3.2 Bluetooth LE and BLE Communication

Bluetooth is a wireless technology for short-range communication, acting as replacement to cables connecting portable and/or fixed electronic devices. Bluetooth features worldwide operation, robustness, low power consumption, low cost, interoperability, etc. The newest Bluetooth version is v5.0. It can be divided into two parts, namely, basic rate (BR) and low energy (LE). Compared to BR, LE preponderates in lower power consumption, complexity, cost, data rates. Thus, BLE is pretty suitable for wearable bio-signal monitoring. The implement modes of Bluetooth are single-mode and dual-mode. Single-mode implementation targets at low power consumption and small size devices while dual-mode, which is an extension to a classic Bluetooth radio, targets at mobile phones and PCs. In this paper, the ECGM is actually implemented by single-mode. The ECGM works as a server and communicates with mobile phones which work as clients. Fig. 6 shows the relationship between bit error rate (BER) and signal-to-noise ratio (SNR) for several popular wireless communication techniques, as well as the normalized power spectrum of Bluetooth LE and IEEE 802.15.4 protocol.

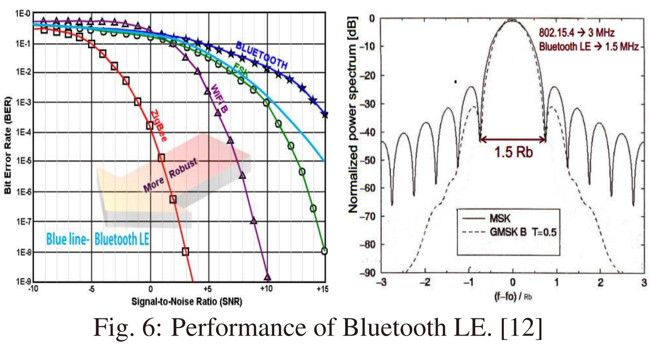

Fig. 6: Performance of Bluetooth LE. [12]

The architecture of Bluetooth is illustrated in fig. 7. The PHY performance is showed in Fig. 6. The LL layer controls the RF state of the device. HCI provides a uniform interface method of accessing Bluetooth Controllers capabilities, including command PHY and LL, access hardware status and control registers. L2CAP provides connection-oriented and connection-less data services to upper layer protocols. ATT is a peer-to-peer protocol between a server and a client while GATT defines how to use the ATT protocol. GAP is a Bluetooth profile which defines the required functions and features of each layer in the Bluetooth system. For BLE, security functions are split between host and controller. In controller, LL provides AES 128 encryption and authentication; In host, SMP defines how to setup a secure link.

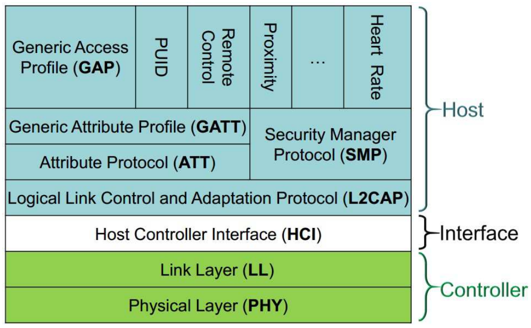

Fig. 7: Architecture of Bluetooth. [12]

To read the digital data stream from BMD101, it is necessary to program in CC2640R2F to realize the main functions: receiving ECG data and communicating with mobile phones. The program framework of Bluetooth LE communication is illustrated in fig. 8. RTOS, which actually means TI-RTOS in this paper, is a real-time operation system for TI devices.

4 Conclusion

In this paper, a low-power wireless wearable ECG monitoring system is proposed based on BMD101 sensor chip and CC2640R2F Bluetooth LE MCU. The wearable telemetry ECG monitoring system includes three parts, namely, ECG monitoring device (ECGM), mobile phone, and the cloud server. The main process is: ECG signals are collected, pre-processed, and digitalized by BMD101 sensor, which acts as a front-end in the ECG monitoring device (ECGM); The digital output packets are received by CC2640R2F through UART, then sent to nearby users' phones for ECG display; The cloud server stores the users' ECG data, supplies telemetry monitoring service for cardiologists, and pushes the cardiologists' advice back to users' phones. Because of the high resolution and low power consumption of BMD101, as well as ultra-low power consumption of CC2640R2F, the proposed system features low power consumption, high signal quality, etc. By the way, The key point in sofware design, how to parse a digital output packet and communicate with mobile phones, is briefly introduced in the software implementation section. A preliminary framework of the designed system is built and furthermore, more details, such as ECG

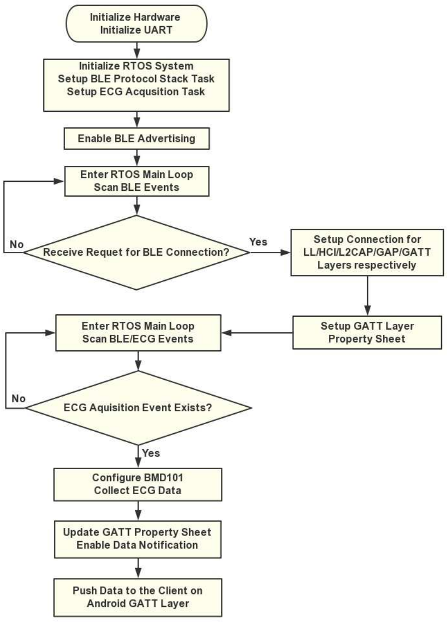

Fig. 8: Program framework of BLE communication.

classification algorithm, need to be studied in the near future.

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