Optimizing data rate and power in BLE network for health care

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Abstract. There is a need for low power high bandwidth connected patient monitoring solution for patients in large volumes with easy deployment. The paper proposes data compression algorithms for optimizing data rate and power in Bluetooth Low energy network. The system is implemented using Bluetooth Low Energy (BLE) devices for data collection from a patient and a gateway to transfer the data to remote computer in an Internet Protocol (IP) network. The compression algorithms are optimized for the ARM microprocessor to compress the recorded values along with time stamps into a block. The sensor module is designed to be wearable continuously reads temperature and Electrocardiogram (ECG) and transmits them to a nearby gateway device. The gateway decompresses the data and uploads them to a cloud infrastructure. The system also allows for intensive monitoring of patient vitals. The collected data is processed and displayed in a moving graph in a remote web terminal. Results indicate that data rate and power has reduced by more than 45% and 3% respectively. With these results it is shown that high bandwidth monitoring solution is feasible with no extra expense in power. This system would be very beneficial to society in terms of affordable medical care as it can be used in large hospitals and remote medical camps alike where the patients can be monitored remotely.

1. Introduction

The use of wearable wireless electronics monitors could cut down the cost in health care industry without compromising patient care. It has been predicted that in future 600 million people globally will suffer from chronic diseases and that spending on such diseases will increase. Therefore, wireless monitoring would replace expensive medical care; improve efficiency and patients’ comfort by moving patient out of hospital wards into the home. It is possible to monitor the patients, families and caregivers to changes in vital signs and missed medications.

Hospital patients are connected to multiple healthcare devices. Using wireless monitoring systems, the vital signs can be transferred directly to hospital’s central monitoring systems [2]. When a patient is in an ambulance and treated by paramedics, data can be sent wirelessly to the gateway inside the ambulance and transferred to the cloud service. Hospitals can get data and be better prepared when the patient arrives at the critical care; BLE meets the requirements such as low data rate, customized software, low-power operation, security of data transferred, robustness, compatibility with most mobile units [3] needed for widespread usage of wireless monitoring. For continuous medical monitoring application very low power consumption is required so the device can run a coin cell battery for months. Moreover, the most innovative characteristic of BLE, in comparison with Classic Bluetooth and other wireless technologies, is the low power consumption [3].

The devices also have much more generalized roles and connection restrictions are limited to the physical characteristics of the device. Data compression is used by wearable devices to reduce power consumption. In this paper the data from Electrocardiography (ECG) and temperature sensors are compressed before transmitting the data from BLE peripheral and decompressed after receiving the data in the BLE central node. The data is transmitted to the cloud and displayed in a format for easy visualization by the doctors, patients and caregivers.

Section 2 gives the Prior work, Section 3 elaborates the System design, Section 4 gives the Experimental Results and Section 5 concludes the work.
2. Related works
Steven Keeping [1] has discussed that BLE can meet all requirements for medical applications. The author has shown how BLE is used for continuously used for monitoring blood glucose level and why other proprietary solutions prove insufficient. Sudheer Babu et al [4] have developed a prototype for measuring ECG signals using BLE devices and Smartphone and have explore the feasibility of a BLE link for meeting the QoS requirements got from discussions with cardiologists. It is a modular and scalable system, and this paper aims to improve upon it for an infrastructure wide deployment. Zhou et al [5] proposes a low power health monitoring system for measuring ECG, respiration, and body temperature. Their sampling rate was at 250 Hz and they connected 3 nodes. They were able to extend battery life to 107 hours with a 1100 mAh 3.7V lithium battery. This paper has excellent performance, but the proposed work aims to improve upon it for better power savings. Yu et al [6] have proposed a system consisting of single-chip ECG signal acquisition module, a Bluetooth module and a Smart phone. The data collected from ECG module is processed and transmitted by the BLE link and displayed in the smart phone. The Smartphone transmits this data through Wi-Fi to the database of the hospital. This work relies on a single Smartphone. This proposed project proposes an infrastructure wide deployment and not for a few patients.

Zhe Yang et al [7] have developed an ECG Monitoring system to collect the data and transmits the data to the cloud using Wi-Fi. Both HTTP and MQTT protocols are used to provide visualization of the data to users. This work uses Wi-Fi, and that kind of power consumption would not be sustainable on a wearable device. A mesh network topology for BLE devices was designed and implemented in [8]. They have shown that latency and power consumption of the proposed BLE mesh is less. But it is not scalable in a scenario with limited gateways in the network, in a large and dense hospital environment like in India and other developing and remote countries and it is inefficient for high bandwidth data streams. Apair BLE 4.2 devices and a raspberry pi were used for transferring temperature and heart rate to server using MQTT protocols in [9]. Compared to the previous works the proposed system uses Data compression algorithm to reduce the amount of data transmitted thus allowing continuous monitoring with very low power consumption.

3. System design
The proposed system provides a low power, cost effective health monitoring system to monitor vitals like electrocardiogram and temperature without compromising accuracy and timeliness and transmits the data to the cloud making it possible to monitor it from remote location. The vitals can be monitored remotely through a website. The server can also be configured to give alert for critical conditions. The main block diagram of the project is shown in the Figure 1.

Figure 1. Main Block Diagram

3.1 BLE peripheral
The peripheral device is a Nordic Semiconductors’ nrf51822 based development board. It has a 32MHz ARM cortex M0 processor with a 2.4GHz Radio peripheral which is used for Bluetooth LE. The device hosts a Generic Attribute (GATT) Sever which contains one attribute for each sensor. The device connects to a Maxim MAX31856 thermocouple-based temperature sensor through SPI, which has a resolution of 0.0078125°C and is connected to a K-type thermocouple which can measure from -200°C to +1372°C. The device is also
connected to an Analog Devices AD7980, a 16 bit 1 million samples per second (msps) Analog to digital converter (ADC) whose input is connected to an Analog Devices AD8232, an analog font-end for ECG signal acquisition. The ECG frontend is connected to electrodes which are attached to the patient. The temperature is sampled at 1 sample per second (sps) and ECG signal is sampled at 1000 sps. The device is programmed to setup and start advertising its presence with BLE. When the central device requests data, the peripheral uploads data through BLE GATT notifications.

3.2 BLE central

The central device is also the same hardware as the peripheral. The central is connected to the gateway through UART. The central starts and waits for commands from the gateway for further action. It can scan, connect, read sensor data, and monitor Received Signal Strength Indication (RSSI) from the remote device(s). The central is programmed to communicate with the gateway through a simple packet-based protocol to monitor multiple data simultaneously. When the gateway requests the central to scan, the latter scans all advertising BLE devices which implement the GATT service of interest and sends the data to gateway. The gateway then responds with a device to connect with. After connection, RSSI, temperature and ECG samples can be acquired and transferred to the gateway, should it be requested.
3.3 Gateway
The gateway is a Raspberry Pi 3B running a python program which communicates with the central device through serial and uploads data to a server implementing a web service to host the data. The Raspberry Pi 3B runs diet-pi operating system to strip unnecessary software with a minimal desktop environment. The python program can also display statistics in command line and graphical interfaces about current values, throughput, and RSSI.

3.4 Web server
The server has three components – a web service, a website host, a database. The gateway uploads data to the database through the web service. The web service commits the data to the database. The website host accesses data from the database and sends the data to the web terminal. The database can host data from many patients and time frames and the queries can be modified to get filtered results. The type of database is a relational database, preferably a cluster or partially in memory database to provide maximum performance for a scaled scenario. The website host is a Grafana dashboard which also hosts the web terminal. The web server has an Intel Xeon E5-2683v3 Processor, 128GB RAM and 8TB of storage.

3.5 Web terminal
The web terminal is essentially a website hosted by the server that can be accessed from any computer that can access the server. The web terminal has a dashboard which has been configured to display the data as a moving graph which refreshes periodically. Many more statistics can be monitored and configured to visualize aggregated data.

Figure 11 shows a snapshot of the dashboard which is viewed from another computer in the intranet showing live data.

4. Algorithm
A modified version of Differential Pulse Code modulation [10] algorithm is used to compress the data. The pseudo code for compression algorithm and decompression algorithm is shown in Figure 5 and Figure 6.

The sampled data is stored in a buffer until the buffer becomes full for compressed data to be equal to the maximum transferrable data size. Data is compressed in blocks with each block having a full sample followed by differential samples which have smaller size. The block sizes are constant before and after compression resulting in constant compression efficiency.

The compressed block size is set to 20 which is the maximum size of the application payload for BLE 4.2 per packet. Each sample is 16bits in size. For a stable person, the heart rate sampled at 1000 sps does not vary by more than ~110 units approximately even with abnormal heart rate. So, the differential value is set as a signed 8bit integer. This results in a simpler packing mechanism for quicker compression and decompression.

With the above parameters to compress to 20 bytes (160 bits), the first parameter is the first full sample of the block and it is followed by difference between successive samples from the previous sample. Preserving the
first sample mitigates any drift that might be induced when calculating the differential values. Thus 18 more samples can be packed as 8bit differential values.

Consider buffer to be the block of samples and payload to be the application payload in the BLE packet.

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**Figure 4.** State Diagram of BLE Central
5. Results and analysis

The performance of the device is monitored closely with an external power profiler, internal algorithms for compression efficiency at the central BLE device and CPU usage of the peripheral to measure impact of compression.

Figure 7 shows the Experimental setup for the proposed prototype.
5.1 Data rate

The data rate was measured on the central BLE device before and after decompression. Since the sample rate remains constant and only the sample sizes remain different, the average data resolution is determined. This value is used to calculate data rate.

Before Compression,

Data rate,

\[ \text{Data rate,} = 1000 \text{ sps x 16 bits} \]
\[ = 16,000 \text{ bits per second (bps)} \]

After Compression,

Apparent Resolution,

\[ \begin{align*}
\text{No of bits} & =\frac{160}{19} \\
& = 8.42105 \text{ bits}
\end{align*} \]

Data rate,

\[ \begin{align*}
\text{Data rate,} & = 1000 \text{ sps x 8.42105} \\
& = 8421.05 \text{ bps}
\end{align*} \]

Compression efficiency,

\[ \begin{align*}
\text{Compression efficiency,} & = \frac{\text{Data Rate before Compression}}{\text{Data Rate after Compression}} \\
& = \frac{8421.05}{16000} \\
& = 52.63
\end{align*} \]

Figure 8 shows the compressed and uncompressed data rate in bits per second with time stamps. The algorithm achieves a compression efficiency of 52.77% for a real-world sample rate of 993 sps for ECG and 1sp for temperature. The lower sample rate in Figure 8 is due to rounding of time interval to a lower resolution and not an impact of compression. The efficiency includes samples from all channels including temperature. But temperature is transmitted uncompressed to prevent unnecessary latency.
5.2 Power Consumption

The power consumption was measured by a power profiler from ZS Circuits (ZS-2102-A). Figure 9 shows the snapshot of the power profile captured by the power profiler. The power was measured for two firmware variant pairs for both the central and the peripheral – with compression enabled and disable.

![Figure 9. A snapshot of the power profile captured by the power profiler](image)

The power was monitored for approximately 20 seconds while transmitting at 1000 sps for each firmware pair. Table 1 shows the average current (mA) for compressed and uncompressed firmware. There is a 2-3% (0.35mA) reduction even with LEDs and other factors and greater for more optimized implementations.

| Device       | Average Current (mA) |
|--------------|-----------------------|
| BLE Peripheral | With Compression: 9.124  
                            Without Compression: 9.439 |
| BLE Central | 8.357  
                            8.756 |

5.3 Received signal strength indicator (RSSI)

RSSI is a measure of the average power of the received radio signal and affects the Signal to Noise Ratio (SNR) of the received signal. For lower SNR, signal noise increases, and overall data throughput decreases due to dropped packets.

By reducing the transmission duration and increasing the transmission intervals it is possible to introduce headway for retransmission for failed transmissions. The RSSI values are plotted for various distances in Figure 10. As Distances increases RSSI values are decreased as shown.

5.4 Temperature and ECG Signal

The temperature and ECG signal can be monitored through from a remote computer connected to the internet with a website. Live data can be monitored with only a latency of less than a second as in Figure 11. The website consists of a dashboard through which graphs of ECG and temperature are displayed for each tracking patient. It is possible to display data in many forms, aggregate all collected data, set alerts for threshold conditions, and customize dashboards for certain patients.
6. Conclusion and future work

The results observed prove that the approach is a logical choice. With the recent improvements in hardware, data can be sampled at more accurate time intervals and with reduced load to the CPU. The latest BLE stack provides for Data Length Extensions with remove overhead by lengthening data packets and reducing redundant transmissions. It is also possible to improve upon the implementation of the algorithm with newer embedded hardware to reduce the load on the CPU further and decrease power consumption. This system can be paired with an extensive medical record system, like Telehealth and Medical Data Recording platforms like openEMR and openMRS and can be deployed in live environment thus providing a low power consumption patient monitoring system to the medical society at large.

Figure 10. RSSI value vs Different Distances Calibrations

Figure 11. A snapshot of the dashboard which is viewed from another computer in the intranet showing live d
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