Customizing 6LoWPAN Networks towards Internet-of-Things Based Ubiquitous Healthcare Systems

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Abstract— **Embedded devices with enhanced communication capabilities, Internet of Things (IoT), are able to perform a wide variety of different tasks at present. One rapidly increasing application domain is healthcare. In this paper, we present an IoT-based architecture and system implementation for healthcare applications. The presented IoT-based system provides a cost-effective and easy way to analyze and monitor, either remotely or on the spot, real-time health data such as Electrocardiogram (ECG) and Electromyography (EMG) data. Health data is transmitted by utilizing IPv6 over low power wireless area networks (6LoWPAN). Our efficient customization of the 6LoWPAN network for health data provides energy efficient and reliable transmission in different scenarios that is required in several healthcare applications.**

Keywords—Internet of Things, e-Health, 6LoWPAN, Wireless Sensor Network (WSN), Remote Patient Monitoring

I. INTRODUCTION

Internet of Things (IoT) is a dynamic network infrastructure, connecting physical and virtual things together. It can have self-configuring capabilities based on standard, interoperable communication protocols and it can use intelligent interfaces to seamlessly integrate things into a network [1]. The IoT enabled applications can be used in several domains such as aviation, automotive, environment monitoring, healthcare, logistics, safety and security monitoring. Owing to the wide variety of application domains, many technologies, such as network technology, data and signal processing technology, as well as security and privacy standards are combined with IoT.

A low-cost and smart IoT enabled healthcare system which has the ability to monitor patients' health remotely using wireless sensors have possibility to improve the quality of healthcare, potentially save patient's life and reduce the overall costs in healthcare. Reducing the cost of healthcare is a significant concern around the world; therefore, the efficient utilization of resources and the unit cost of healthcare services and devices have to be considered. Solely, the obesity among the people increased exponentially over 3 decades and reached 500 million which resulted in several illnesses such as cardiovascular and diabetes [2]. Also the aging of population and hereditary ailments increase healthcare expenses. For instance, $1.5 trillion was spent annually for medical care in United States [3].

Wireless sensor networks (WSNs) play important roles in many applications in industry, entertainment, healthcare and many other areas. Especially, IEEE 802.15.4 standard [4], which offers physical layer and media access control for wireless personal area network, is widely used due to its low-cost and low-power consumption. Many protocols such as ZigBee and other custom protocols are constructed on top of the IEEE 802.15.4. However, with all these protocols, interoperability of smart devices remains a challenge as they are not IP-based. In order to mitigate this interoperability problem, an evolved network IP-based protocol called IPv6 Low-Power Wireless Personal Area Network (6LowPAN) [5] was proposed which extends IP to low-power WSNs. 6LoWPAN provides many advantages such as scalability, mobility, low-cost, low power consumption, due to exploiting the existing IP network infrastructure and without requirements for dedicated packet translation gateways or proxies. In addition, 6LoWPAN offers efficient header compression and reduced packet size compared to traditional IPv6 networks. Furthermore, it inherits IPv6's auto configuration. Our proposal in this paper is motivated by these advantages of 6LoWPAN networks to be customized and utilized in our IoT-based ubiquitous healthcare system.

In this paper, we present a customized 6LoWPAN network for IoT-based ubiquitous healthcare systems. The aim is to implement the entire architecture for healthcare environments starting from collecting bio-signals using analog front-end (AFE) devices integrated in 6LoWPAN medical sensor nodes to finally present health and contextual data stored in a cloud server to end-users. In addition, we elaborate the architecture's services and customize 6LoWPAN for healthcare systems from the viewpoint of real-time streaming data, reliable transmission and cost efficiency. The key contributions of this work are as follows:

- A complete IoT-based healthcare system implementation from AFE to end-users
- Customized 6LoWPAN network targeted for the e-Health related data
- A tunnelling gateway for routing packets from nodes to a server in the Internet (traditional IP network)
- A WebSocket server for real-time health data analysis at the cloud

This paper is organized as follows. In Section II, the related work and the motivation are discussed. Section III provides an overview of our e-Health system architecture focused on 6LoWPAN. Section IV describes the system implementation in more details, while Section V demonstrates the experimental results. Finally, Section VI concludes the paper and discusses some directions for future work.

II. RELATED WORK AND MOTIVATION

In the IoT-based healthcare system, different bio-signals such as Electrocardiogram (ECG), Electromyography (EMG), body temperature, Peripheral capillary oxygen saturation (SpO2), blood pressure, respiration, glucose and contextual data are sensed and transmitted over a network via wired or wireless interfaces. These data are streamed and then remotely monitored by different caregivers such as medical doctors. Based on this data, patients' health conditions are manually or automatically examined and appropriate feedbacks are provided. Thus, health data being extremely critical in healthcare environments, must fulfill strict requirements defined by IEEE 1073 (i.e., X73) group shown in Table 1 [6].

TABLE I. Data rate of various bio-medical signals

Bio-medical Signal	Latency	Data Rate
Blood pressure	< 3 s	80 - 800 bps
Pulse / Heart Rate	< 3 s	80 - 800 bps
Glucose	< 3 s	80 - 800 bps
Temperature	< 3 s	80 - 800 bps
Respiration	< 300 ms	50 - 120 bps
SpO2	< 300 ms	50 - 120 bps
ECG	< 300 ms	3-lead (2.4 kbps), 5-lead (10 kbps), 12-lead (72 kbps),

Most of the research efforts focusing on IoT architectures in healthcare environments often use ZigBee, Wi-Fi, and RFID technologies. For example, Wu *et al.* [7] propose a healthcare management platform based on ZigBee WSN for safety monitoring capabilities. In another effort, Tsirbas *et al.* [8] present a RFID-IPv6 based scenario in a healthcare environment. Their platform utilizes the combination of RFID technology and IPv6 with Virtual MAC address Generator. None of these discussed platforms consider the characteristics of health data such as streaming nature of ECG and EMG data which plays a critical role in healthcare systems. Kirbas *et al.* [9] describe a web-based remote monitoring interface called HealthFace for medical healthcare systems based on wireless body area sensor network. Healthface can be accessed everywhere, anytime via IP based devices without any special programs or requirements for web-browsers.

There exist also some works presenting architectures based on 6LoWPAN. For instance, Kim *et al.* [10] propose a framework to support network-based mobility of 6LoWPAN sensor devices for mobile healthcare. Jara *et al.* [11] present intra-mobility for hospital wireless sensor networks based on 6LoWPAN. However, they only focus on mobility of network without considering the real-time requirements of health data in healthcare environments and nodes' battery life time. Touati *et al.* [12] describe an indoor 6LoWPAN based platform for real-time healthcare monitoring, demonstrated by using an ECG simulator and Labview [13] for user interface. The presented platform has many limitations: i) ECG data is not received from any real analog front-end device, ii) their gateway requires to be connected to a computer for tunnelling from the 6LoWPAN network to the wide area network, and iii) end-user needs a computer having Labview software installed on it.

The main motivation of this paper is to provide an enhanced IoT architecture based on customized 6LoWPAN for healthcare environment. The major difference from previous work is that we present a complete architecture having extended node battery lifetime from analog front-end devices to final end-users with many necessary services fulfilling strict requirements of real-time health data. The related works have not considered node battery lifetime being one of the most important aspect in a wireless sensor network. Besides, our architecture offers several services such as node's battery state-of-charge notification, node's temperature notification, lead-off connection between electrodes, and patient-notification. Compared with the conventional e-Health platforms, our platform is more efficient in terms of scalability and energy consumption. In addition, we provide web-based user interface which is supported by many devices such as computers, PDAs, and smart phones.

III. SYSTEM ARCHITECTURE

The architecture of our IoT-based health monitoring system is shown in Fig. 1. The proposed architecture comprises sensor nodes, a gateway, a server and clients. A sensor node gathers patient's bio-signals (health data) which it then sends through a gateway to a server. The server stores and processes the gathered data. An end-user, either a healthcare professional or a layman, can then view the processed or raw data in his/her web client (e.g., smart phone, table, or a laptop).

The health data can also be supplemented with context information, for example, location, humidity, and temperature. Associating the context information with bio-signals provides more information for healthcare professionals to make their medical treatment plan.

As stated above, the medical sensor nodes gather users' bio-signals. To do that, a node is composed of the following sub-modules: i) electrodes (not shown in Fig. 1), ii) AFE and Analog-to-Digital Converter (ADC), iii) Microcontroller Unit (MCU), and iv) a RF transceiver. The main functions of these sub-modules are: i) The electrodes collect bio-signals, ii) ADC converts the signals from analog to digital format, iii) MCU pre-processes and packetizes data to 6LoWPAN packets., and iv) the RF transceiver module transmits the data to the gateway.

The gateway forwards the health data to the remote server. It provides tunnelling between 6LoWPAN and IPv4/IPv6 protocols providing seamless extension of the existing IP networks to encompass resource-constraint sensor networks. Each medical sensor node is assigned with a unique IPv6 address. The higher 64bits of the IPv6 address are hardcoded and the remaining 64bits carries an ID generated from a MAC address. The ID is generated when the medical sensor node begins its operation, and it is used to prevent IP address duplication. In addition, the gateway is armed with several features such as local data repository, processing capability, and user notification to save bandwidth and enhance the system reliability especially during the times of unavailability of the Internet.

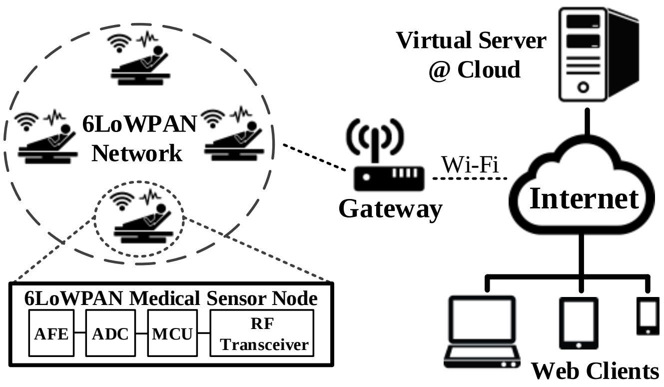


Fig. 1. **IoT-Based Healthcare System Architecture**

Web clients and virtual server forms a back-end system whose responsibilities are: i) the virtual server at a cloud offers data storage, big data processing, push-notifications, and WebSocket services and ii) Web clients provide easy-to-use graphical user interface for visualization of health data.

IV. System Implementation

In this section, we present the system implementation of our IoT-based healthcare system in three phases: sensor nodes, gateway, and the back-end system.

A. *Sensor nodes*

The core of the medical sensor node is TI CC2538 SoC [14] which has a powerful ARM Cortex M3-based 2.4 GHz MCU, IEEE 802.15.4 compliant transceiver radio, 512 kB flash, 32 kB RAM, 32 GPIO, and SPI. It also has battery monitor and temperature sensor making it ideal for our system. In addition, CC2538 has an AES-128/256, SHA2 hardware encryption engine that allows us to expand our architecture with security features.

The MCU sub-module receives data from the AFE sub-module though an SPI connection. The AFE sub-module is TI ADS1292 AFE [15] device which is a low-power, 2-channel, 24bit AFE with 2 low-noise PGAs and 2 high-resolution ADCs. In ADS1292, analog data from electrodes is converted into a digital form. Owing to low power consumption, fast and accurate ADC and low noise signal, ADS1292 is ideal for health data.

As discussed above, the communication between MCU and AFE is implemented using an SPI connection. In the communication, CC2538 node is configured as a master while ADS1292 is set as a slave. The communication is synchronised by a 2 MHz clock generated by CC2538. In order to get data from ADS1292, CC2538 must set ADS1292 to one of the three communication modes: continuous, read-data-by-command, and reading register mode. In our implementation, we applied continuous mode. In the continuous mode, ADS1292 shifts out digital data to CC2538 when the data is ready after the analog to digital conversion process. ADS1292 gets analog data from 3 leads including 2 analog channels and a reference channel. The implementation of the medical sensor node with ADS1292 is described in Fig. 2.

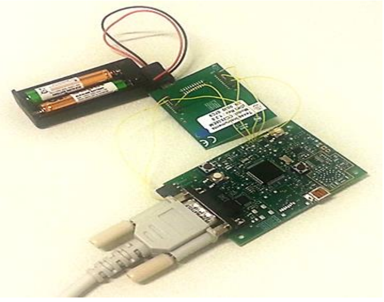


Fig. 2. **Medical sensor node based on TI CC2538 with TI ADS1292**

The ARM Cortex M3 runs up to 32MHz speed and has 512 kB flash memory, which makes it suitable for running an operating system. In our system, we use Contiki operating system [16]. Contiki is developed for low-power internet of things devices making it ideal for our system. The operating system manages and schedules all tasks including communication related tasks such as reading data from the AFE devices, generating and receiving UDP packets over 6LoWPAN network.

1) *Operational reliability*

To notify the system and its end-users of a low charge level in the battery, we implemented a warning message mechanism. The mechanism has three levels: 10%, 5% and 1%. When battery level reaches 10% and 5%, the node will generate a warning message to a router, and if the battery level goes further down to 1%, the node will create a critical message which will be treated as high priority in our system. The battery notification mechanism was implemented by using CC2538's inbuilt battery measurement sensor with interrupt service routine. In addition to the low battery indicator, a high temperature indicator for an on-chip temperature was implemented. The threshold temperature was set to 50 degrees. After reaching 50 degrees of Celsius, the indicator generates a warning message. As for low battery indicator, we used the inbuilt temperature sensor with interrupt service routine to implement the high temperature indicator.

The connection between electrodes and a patient' body is also of high importance. The connection between electrode and patient's body must be properly conjoined because weakness in the electrode-patient conductive path affects the input impedance. In order to reduce the inaccuracy in the ECG signal due to poor contact between electrodes and patient, we implemented a lead-off detection service. The service sends messages to the gateway when the connection between electrodes and a patient is not properly done. The service was implemented by using the interrupt services routine. However, we were not able to generate a warning message with specific information of a particular failing connection due to the limitation of the number of interrupt pins in CC2538. Therefore, we only created a warning message representing that one connection is not properly connected. These messages will be handled by a push notification service implemented in the gateway and/or the server.

2) *Energy Efficiency*

To reduce the power consumption, we filter data in the medical sensor node by checking the minimum and maximum heart rates as well as peripheral capillary oxygen saturation levels set by American heart association and Nonin medical [17][18]. In terms of power consumption, filtering heart rate data increases power consumption; however, applying these filtering methods reduces the power consumption in communication [19]; notwithstanding, the total power consumption of filtering and transmitting data is less than transmitting raw data.

B. *Gateway*

Our Gateway is implemented by integrating a Pandaboard [20] and sink node which in turn is a composition of CC2538 module and SmartRF06 board as shown in Fig. 3.

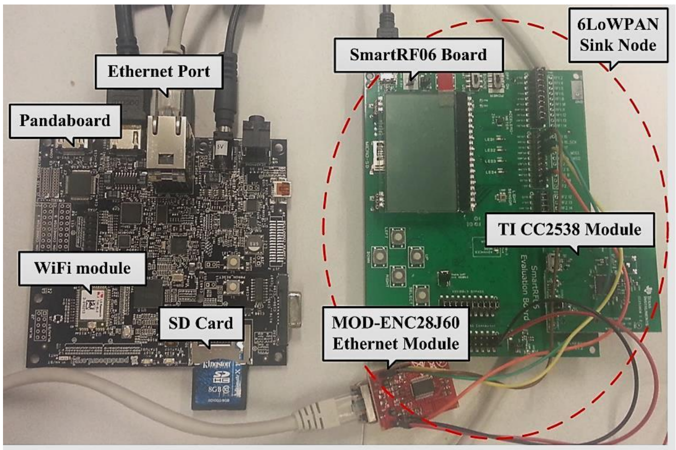


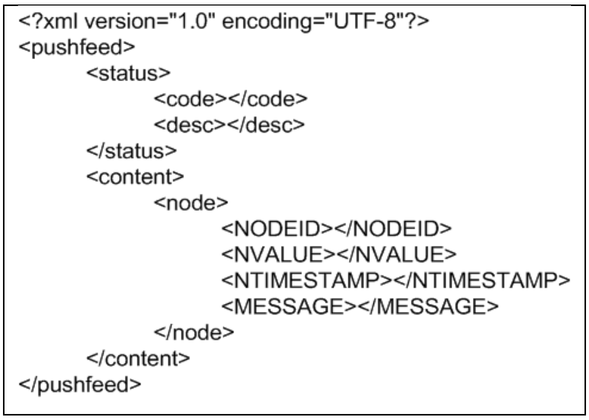
Fig. 3. Gateway Implementation

The Pandaboard is the core for our gateway, it based on OMAP4430 platform comprises of integrated on-chip memory, external memory interfaces, peripherals interfaces and Cortex A9 microprocessor unit including dual core ARM Cortex A9 cores with symmetric multiprocessing at up to 1.2 GHz each. It supports different network standards such as Ethernet, 802.11b/g/n and Bluetooth, and operating systems such as Windows CE, Symbian and Linux. The CC2538 module is attached to TI SmartRF06 board - an ARM Cortex-M based System-on-Chip (SoC) - to form a sink node. Olimex Ethernet module [21] is used to establish Ethernet connection between the SmartRF06 board and the Pandaboard to enable data transfer between them.

The Ubuntu operating system empowers the Pandaboard to accomplish its functionalities by providing platform for implementation and also enables us to have several applications. Other than UDP server implementation, we installed MySQL database to store the copy of received data temporarily in the gateway. The notification framework tables in the gateway are created using federated engine which allows us to create reference for the records available in the server without database replication and provides automatic data synchronization while giving less priority to manual synchronization. This allows the notification service to continue its operation in the case of internet unavailability.

C. *Back-end System*

For the server, we used a free hosting service for our demonstration. The back-end is MySQL database, PHP used as server-side scripting and JavaScript (JQuery) for HTML content generation such as plotting charts. We also developed an Android application for notification and appropriate web services in the server for information retrieval. The notification web services receives request and returns XML as response. The structure of the XML response is described in Fig. 4 and the explanation of the status codes are given in Table 2. The received XML is parsed in the Android application and a notification is raised based on the status section of XML response.



```
<?xml version="1.0" encoding="UTF-8"?>
<pushfeed>
        <status>
                <code></code>
                <desc></desc>
        </status>
        <content>
                <node>
                        <NODEID></NODEID>
                        <NVALUE></NVALUE>
                        <NTIMESTAMP></NTIMESTAMP>
                        <MESSAGE></MESSAGE>
                </node>
        </content>
</pushfeed>
```

Fig. 4. Response in XML Format

TABLE II. XML Status Section's Code and Description

Code	**Description**
0	Invalid Request or Error
1	Notification – {total in number}
2	No New Notification

V. EXPERIMENTAL RESULTS AND DEMONSTRATOR

As mentioned before, meeting real-time requirements is essential in e-Health applications. To efficiently customize our system to honour these requirements, we need to guarantee that all the data in our architecture, from medical sensors nodes to end-users, fulfils requirements of the IEEE 1703 standard for health data. To this end, we follow the requirements and specifications (e.g., date rate, latency) shown in Table 1 for different health sensors such as ECG, SpO2, and hearth and respiration rate. In our demonstration, to analyse the impact of environment and distance among nodes for the network power consumption and system reliability, we setup four different scenarios in which our 6LoWPAN-based network is comprised of 8 nodes and a standalone gateway, but with different configurations. These scenarios are illustrated in Fig. 5.

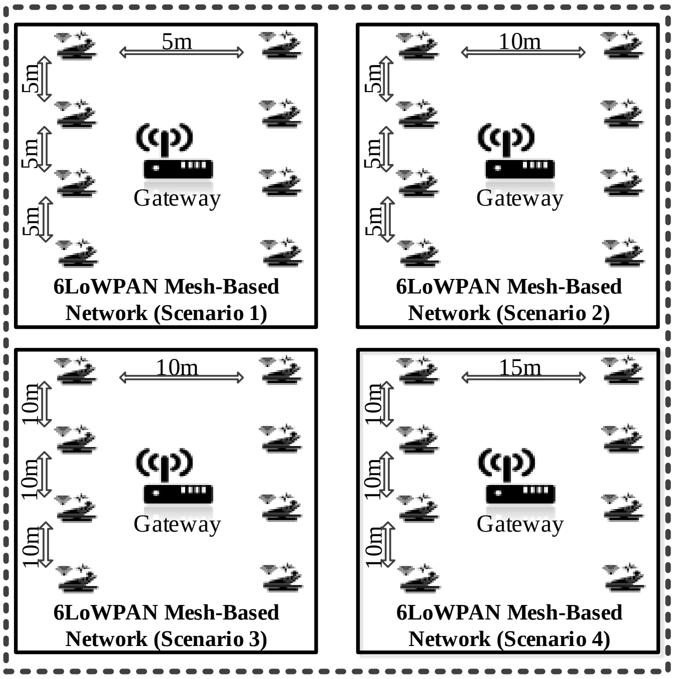


Fig. 5. Experimental setup scenarios

The sensor nodes and the gateway are allocated in a room with distances varying from 5 to 15 meters. All sensor nodes are configured to send a set of health data including 3-lead ECG, SpO2, Blood Pressure, Heart Rate, Temperature, Respiration and Glucose, which together needs 8.7kbps of data rate. This data rate was calculated according to the specifications of IEEE 1073 standard. Fig. 6 shows the average node power consumption for the different scenarios where reliable transmission was ensured for all the scenarios.

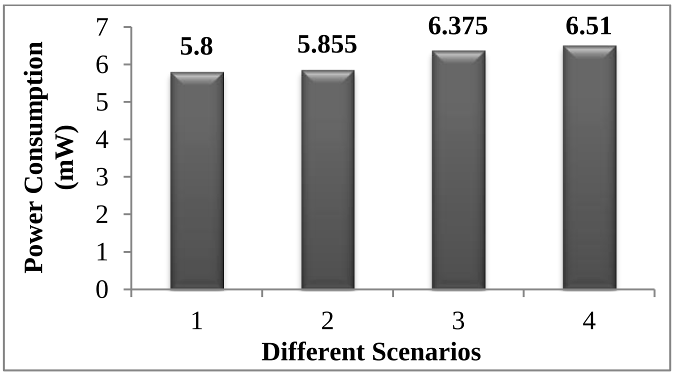


Fig. 6. Average node power consumption transmitting 8.7kbps for different scenarios

The power consumption is measured based on 3.3V power supply. As expected, the 6LoWPAN network offers a low power consumption characteristic as compared to other IP based networks such as Wi-Fi where the average power consumption for the same scenarios is in the range of 14-20mW (when low-power RTX4140 Wi-Fi module [22] is used).

The other reason of having lower power consumption is that instead of configuring the MCUs to operate at 32MHz, we set the MCUs' operating frequency to 8MHz. This clock downscaling is possible when the required data rate is less than 32kbps. Based on the results shown in Fig. 6, we calculate our nodes' battery lifetime which varies from 650 to 700 hours depending on the scenario when applying two AAA Alkaline batteries having the capacity of 750mAh as power supply.

In order to assess the scalability of our system, we added intermediate nodes (INs) which act also as a bridge between a subset of nodes and the gateway, shown in Fig. 7. The intermediate node receives all the health data sent simultaneously from other nodes and then transmits this data along with its own health data to the gateway. Based on our experimental results, an IN can transmit its own data and simultaneously forward (i.e. route) the data coming from up to 17 other nodes when the transmission rate for each node is 8.7kbps. This shows that our system has a high level of scalability to accommodate tens of nodes in a multi-hop manner.

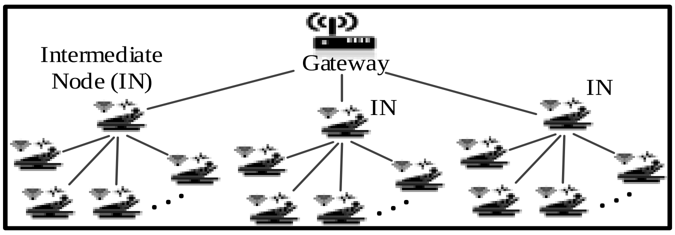


Fig. 7. Experimental setup with intermediate nodes

A snapshot of the implemented IoT-based healthcare system is shown in Fig. 8. In the figure, a 3-lead ECG data is being captured by the ADS1292 analog front-end device, and sent to the gateway where the data is manipulated and updated in the remote virtual server at the cloud. Finally, the graph of the real-time ECG data is plotted in a PDA device.

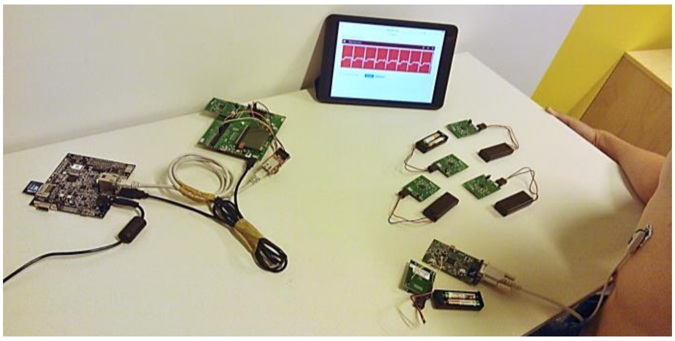


Fig. 8. Demonstration of our IoT-based healthcare system

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we presented an enhanced IoT architecture based on 6LoWPAN for healthcare environments to improve the quality, effectiveness and overall costs in healthcare. The implemented IoT-based architecture is a complete system starting from collecting bio-signals using analog front-end devices integrated in 6LoWPAN medical sensor nodes to finally present health and contextual data stored in the cloud server to end-users. This also includes a tunneling gateway for routing packets from nodes to the server in the Internet and a WebSocket server for real-time health data analysis at the cloud. We also examined the architecture and power consumption for different scenarios. We verified that our architecture is suitable for applications with streaming data in healthcare environments. In future research, extra layer will be added to the 6LoWPAN stack for improving efficiency and level of security. Furthermore, additional data filtering and data compression algorithms will be applied at node level for saving battery power and network bandwidth.

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