2014 Health Innovations and Point-of-Care Technologies Conference
Seattle, Washington USA, October 8-10, 2014

Bluetooth Low Energy for Wearable Sensor-based Healthcare Systems

Ting Zhang, Jiang Lu, Fei Hu, *Member, IEEE* and Qi Hao, *Member, IEEE*

***Abstract*— Wearable sensor-based healthcare systems have drawn a lot of attention from the scientific community and the industry during the past several years. As the healthcare cost is increasing and the population is aging, unobtrusive, low cost and accurate healthcare systems will potentially transform the future of healthcare. They are convenient to use, and can be utilized directly from home or community. These systems have various functionalities, such as bio-signal monitoring, signal analysis and biofeedback. They are consist of subsystems including sensors, data aggregators, data processing units, connected by wired or wireless communication modules. The developing goal of the systems includes to increase the performance accuracy, to make the system smaller, to prolong the battery life and to lower the product cost. Bluetooth low energy (BLE), comparing to traditional wired or other wireless communication modules, is beneficial for these design goals. Devices with bluetooth low energy are attracting more scientists and engineers in research and are changing individuals' lives with products such as wearable sport bends, smart toothbrushes, and intelligent watches. In this paper, we provide an overview of the state-of-the-art Bluetooth low energy technology. Further, we list and analyze the most popular commercial products and the available developing tools.**

***Index Terms*— Healthcare systems, Wearable technologies, Wireless communication, Bluetooth low energy, Biomedicine.**

I. Introduction

WEarable sensor-based healthcare systems have drawn increasing attention from the scientific community and the industry world. Traditional healthcare systems are usually located in a hospital or a clinic environment. The measurement and treatment always need the attention and care from a nurse or a doctor. Healthcare costs can be high when the systems are expensive and the measurement and treatment require plenty of effort from healthcare professionals [1]. Wearable healthcare systems provide an alternative for traditional healthcare. They can be unobtrusive, accurate, low cost, and provide all-day and any-place functionality.

Wireless communication for wearable sensor systems, compared to wired ones, is more convenient for the user. Systems with wireless communications is more likely to be unobtrusive and user friendly. Started from more than 15 years ago, the Internet of Things (IoT) theorized objects and people would connect wirelessly. According to ABI research, by 2020, 30 billion devices will enter into the IoT ecosystem [2]. Seamless device connectivity is an essential technology for achieving a Human-Centric Intelligent Society. Bluetooth technology is one of the frequently used wireless technologies. Bluetooth low energy provide a provide a communication platform has much lower power consumption [3]. This feature enable the devices to run a longer time without a recharge or the battery, and further more, the volume of the device is much smaller because of the shrinking of the size of the battery.

In this paper, in section II, we provide an overview of the concept of wearable healthcare systems and wireless technologies. In section III, we introduce bluetooth technology and bluetooth low energy. In section IV, we gather applications of bluetooth low energy in the market. In section V, we describe the development tools and methods with bluetooth low energy. Section VI is conclusions and discussions.

II. Wearable Healthcare Systems and Wireless Communication Technologies

A. *Wearable Healthcare Systems*

Fig. 1 shows the architecture of a typical healthcare system. The user can be with these light weight, unobtrusive systems in various environments, such as outdoor, at home or in a clinic. The foundation of the systems are the sensors [4]. The sensors make it possible to have access to bio-signals such as motion signals [5], [6], electroencephalogram (EEG) [7], electrocardiography (ECG) [8], electromyography (EMG) [9] or oxygen saturation (SPO_2) [10].The center of the systems are the data collection and data processing units. Data collection and data processing can be done on the sensor chip, or a cell phone or a computer. The hardware with computation capabilities have functionalities, such as monitoring, analyzing, or providing biofeedback. Fig. 1 shows three basic architectures of the system. Architecture I uses a computer for data aggregation and processing. Architecture II uses a cell phone for data aggregation and processing. Architecture III uses a cell phone for data aggregation and the computer for data processing. The sensor system, the phone and the computer are communicated through either wired or wireless communication.

B. *Wireless Communications*

Wireless communication between the user and the data aggregator can make the wearable system more convenient. In general, this involves the technology of wireless local area network. This is related with the IEEE 802 family of standards. The number 802 is associated with the date the first meeting was held - February 1980. IEEE 802.11 defines wireless local area network (WLAN) and mesh network (WiFi), IEEE 802.15 is wireless personal area network

Ting Zhang, and Jiang Lu are with Department of Electrical and Computer Engineering, The University of Alabama, Tuscaloosa, AL, 35487, USA.

Fei Hu and Qi Hao are with Department of Electrical and Computer Engineering, The University of Alabama, Tuscaloosa, AL, 35487, USA. Email: fei@eng.ua.edu, qh@eng.ua.edu.

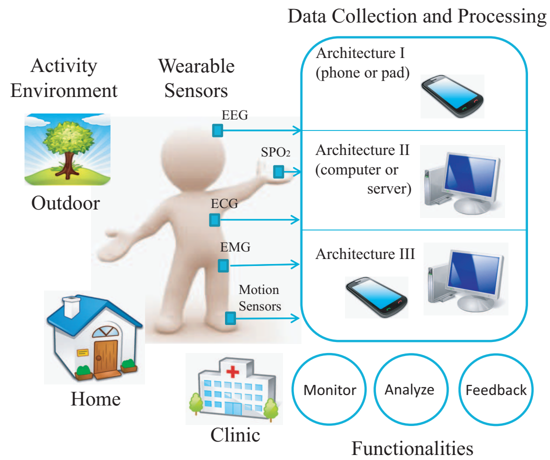

Fig. 1: Wearable healthcare systems.

(WPAN). Typical ones included are IEEE 802.15.1 Bluetooth certification, IEEE 802.15.3 high-rate wireless PAN, like ultra-wide band (UWB), IEEE 802.15.4 low-rate wireless PAN, like ZigBee. There are other wireless technologies, such as Near field communication(NFC) [11].

Wi-Fi is a technology that allows an electronic device to exchange data or connect to the internet wirelessly using 2.4 GHz UHF and 5GHz SHF ratio waves. Wi-Fi is usually access point-centered, with an asymmetrical client-server connection with all traffic routed through the access point. UWB is a radio technology which may be used at a very low energy level for short-range, high-bandwidth communications using a large portion of the radio spectrum. It was traditionally used for non-cooperative radar imaging. ZigBee is a low-cost, low-power, wireless mesh network standard. It has a transmission range about 10 to 100 feet. NFC is a set of standards for smart phones and similar devices to establish ratio communication by touching them together or bringing them to no more than a few inches [3].

III. Bluetooth Technology and Bluetooth Low Energy

A. *Bluetooth Technology*

Bluetooth is a wireless technology standard for exchanging data over short distances. When telecom vendor Ericsson invented it in 1994, it was designed for a wireless alternative to RS-232 data cables. Bluetooth is managed by the Bluetooth Special Interest Group (SIG)[12]. When a device is marketed as Bluetooth, It must be follow the standards of the SIG. It uses short-wavelength UHF radio waves in the Industrial, Scientific and Medical (ISM) band from 2.4 to 2.485 GHz. It uses a radio technology called frequency-hopping spread spectrum. The transmission is based on packets, with a target of one of the 79 designated Bluetooth channels. The modulation method was originally Gaussian frequency-shift keying (GFSK), while $\pi/4$ -DQPSK and 8DPSK modulation was also used. The structure of Bluetooth is master-slave structure. The number of slaves for a master can be up to seven. One slot is 625 μ s intervals. In a simple-slot packets case, the master transmits in even slots and receives in odd slots. The slave receives in even slots and transmits in odd slots. At a time, the master can transmit data to one slave. When there are several slave available, the master switches rapidly from one device to another in a round-robin fashion. Bluetooth protocol stack is a layer architecture consisting of core protocols, cable replacement protocols, telephony control protocols, and other adopted protocols. Newer version of Bluetooth has enhanced data rates. The data rate is 1Mbit /s to 24Mbit /s. A Bluetooth stack is a software that implement the Bluetooth protocol stack. A variety of general-purpose implementations and embedded system implementations are available. For example, Linux operating system currently has BlueZ, initially, Window has Widcomm, and Mac OS X has an integrated Bluetooth stack.

B. *Bluetooth Low Energy*

In June 2010, Bluetooth SIG completed the Bluetooth Core Specification version 4.0 (Bluetooth Smart). It includes Classic Bluetooth, Bluetooth high speed and Bluetooth low energy. Bluetooth high speed is based on Wi-Fi, and Bluetooth low energy is an entirely new protocol stack for rapid build-up of simple links[13]. In late 2011, the name Bluetooth Smart Ready is used for hosts and Bluetooth Smart is used for sensors. Table I shows the comparison of technical specifications of classic Bluetooth and Bluetooth low energy. Bluetooth low energy has wider communication range, much lower power consumption, and lower data rate. While the lower data rate may still meet the need of some wearable healthcare systems, the lower power consumption feature will enable a single battery change to last for a much longer time and the size of the battery can be much smaller. The new bluetooth stack has unique features enable these functionalities. Fig.2 shows the structure of a typical Bluetooth low energy stack.

TABLE I: Comparison of Technical Specifications of Classic Bluetooth and Bluetooth Low Energy

Technical Specification	Classic Bluetooth	Bluetooth Low Energy
Distance/Range	100 m (330 ft)	>100 m (>330 ft)
Data rate	1-3 Mbit/s	1 Mbit/s
Application throughput	0.7 - 2.1 Mbit/s	0.27 Mbit/s
Active slaves	7	implementation dependent
Power consumption	1 as the reference	0.01 to 0.5
Peak current consumption	<30 mA	<15 mA

The BLE protocol stack is composed of two main parts: the Controller and the Host. The Controller is consists of Physical Layer and the Link Layer, and the host includes upper layer functionality. The controller is usually implemented as a small system-on-chip and the upper layer runs on an application processor. The upper layer includes Logical Link Control and Adaption Protocol (L2CAP), the Attribute Protocol (ATP), the Security Manager Protocol (SMP), the Generic Attribute Profile (GATT), and the Generic Access Profile (GAP). Physical layer defines 40 Radio Frequency (RF) channels with 2MHz channel spacing. A adaptive frequency hopping mechanism is used and a Gaussian Frequency Shift Keying (GFSK) modulation is implemented.

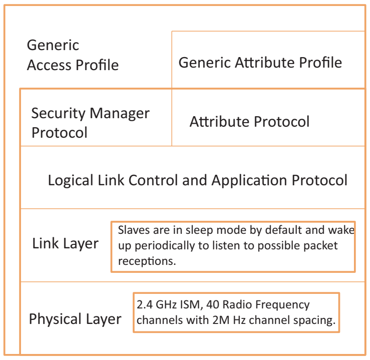

Fig. 2: A typical Bluetooth Low Energy protocol stack.

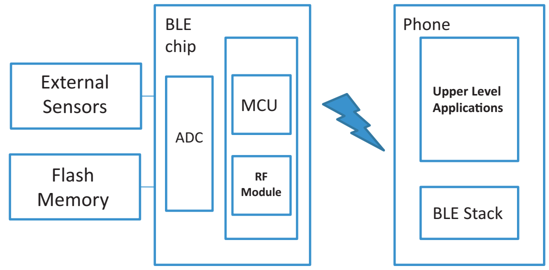

Fig. 3: Hardware architecture of Bluetooth low energy enabled healthcare systems.

The link layer transmits the data between two devices. The transmission includes two steps, the creation of a connection, and the transmitting of the data. BLE defines two device roles for creating the connection, the master and the slave. When transmitting the data, the slaves are in sleep mode by default and wake up periodically to listen or possible packet receptions from the master. L2CAP multiplex the data based on the received data for higher layer protocols. The ATT defines the communication between two devices playing the roles of server and client, and GATT uses the ATT for discovery of the services and exchange of the data, including values and properties. SMP manages security with various security services. The BLE GAP is the highest level of a BLE stack, with the functionalities of management of the established connection and security [3].

From the time Bluetooth 4.0 was introduced, wearable healthcare devices have been invented. Table II shows some example commercial available devices. The designs goals of these devices are different. For fitness, the Training shoes and the sensor socks can measure postures and activities. For sleep monitoring, the Activities by Jawbone can monitor sleep and wakeup times. For bio-signal monitoring, signals including EEG, ECG, EMG, and SPO2 can be monitored and some of the systems can provide biofeedback. The systems are usually smaller, lighter weight and more convenient to wear compared to the ones with classic bluetooth. These systems can communicate with a smartphone or a pad for displaying the monitoring results or provide biofeedback. Selected devices with Android or iOS operating systems already bluetooth smart ready.

IV. Using Bluetooth Low Energy to Develop Healthcare Systems

Recently, various personal computers and mobile devices are bluetooth smart ready. Windows 8 machines with Bluetooth 4.0 controllers, android phones with Android OS 4.3 or later, Apple iPhone 4S and the new version of Apple Mac OS X Lion can be used for BLE development. The mini development kits for BLE include TI CC2540 mini DK, CSR starter development kit, Nordic nRFGoStarterKit, and Nordic nRF8001 Development Kit. The following sections show the hardware and the software development for a wearable healthcare system with BLE.

A. Hardware Development

System on chip (SoC) are the bare-bones microchips manufactured by companies that specialize in integrated circuits. For example, nRF8001 by Nordic Semiconductor and CC2540 by Texas Instruments are such components. To develop with these chips directly is not easy as these chips are usually in a very unfriendly quad flat no-lead package, with tiny pins underneath the chip. Also, the developer needs to add more components, such as crystal, antenna, capacitors, resistors, and a custom metal FR shield. The cost can be high. As an alternative, the turnkey module, are easier to work with. Examples are the Bluegiga BLE112 and BR-LE4.0-S2A. They are from Blueradios and the components are already wired together on a circuit board. The nRF 8001 requires an external application micro-controller for it to operate with a simple serial interface. A typical data acquisition device includes sensors, micro-controller, and a RF module.Fig.3shows a typical architecture of BLE healthcare systems.

B. Software Development

The software system may have the functionalities of monitoring, analysis and providing biofeedback. This typically involves two software modules. One is the data analysis module, and one is the user interface module. The data analysis module is usually originally developed on a PC for training and testing. The user interface module runs on the phone. The software system architectures are usually as the followings. After the bio-medical signals are collected, they are sent to a computer for training and validation. The training process can provide a model to effectively analyze the data and the validation process will show an estimated system performance. The model for analyzing the data is programmed into the application running on the phone. This application is based on BLE stack as a background service gathering the data, and process the data with the data analyzer. The user interface displays the raw signals, analyzed signals and may provide biofeedback.

V. Conclusions And Discussions

Sensor technologies, low power communication modules, and intelligent mobile devices make it possible for healthcare systems to be light weight, unobtrusive, and usable without

TABLE II: Commercial Available Healthcare Devices Using Bluetooth Low Energy*

Product name	Functionalities	Data aggregator	Company	System Review and Critical Analysis
UP 24 [14]	Monitoring posture and activities tracking sleep and wake up time	Android 4.3 (or later) and iOS (6.0 or later)	Jawbone	The system is a in a waistband shape and has multiple functions
Smart Blood Pressure Monitor [15]	Monitoring Blood Pressure	iPhone 5	Withings	Measure blood pressure in one gesture and display results in an iphone
Heart Rate Sensor [16]	Monitoring heart rate with ECG sensors	iPhone 4S (or later)	Polar	Provide heart rate monitoring and training applications
Kinetic inRIDE Watt Meter	Measuring heart rate, cadence, speed and distance	iPhone 4S (or later)	Kinetic by Kurt	The Heart rate zones in the phone shows heart rate and total time training
ditto Bluetooth LE	Measuring glucose	Android 4.3 (or later) and iOS (6.0 or later)	Biomedtrics	Sync data with several compatible FDA approved blood glucose meters
Training Shoes [17]	Measuring gait related parameters	iPhone 4S (or later)	Nike	The shoe features an embedded sensor in the sole
Fitness Socks	Measuring gait related parameters	Android 4.3 (or later) and iOS (6.0 or later)	SensoRia	The socks are light weight and convenient to wear
Wireless EEG headset[18]	Monitoring EEG signal	Android 4.3 (or later) and iOS (6.0 or later)	Imec et. al	The wireless low power EEG is convenient to wear
Body patch[18]	Monitoring ECG signals	Android 4.3 (or later) and iOS (6.0 or later)	Imec et. al	The ECG can have up to 3 leads
Finger Pulse Oximeter [19]	Measuring SpO2	iOS (6.0 or later)	Nomin Medical	The pulse oximeter can provide feedback if not positioned correctly
EMG2Go [20]	Measuring EMG signals	Android 4.3 (or later) and iOS (6.0 or later)	Texas Instruments	It is designed to measure EMG, but can also measure EEG and EGO

*The content of the table is from various company websites. The summery of the products is from our own knowledge. Our opinion does not reflect the opinion of the manufactures.

location constrains. In this paper, we provide an overview of the wearable healthcare system technologies with a focus on the Bluetooth low energy technology. We summarizes of various commercial available wearable healthcare devices with Bluetooth Low Energy and provide an overview of the methods of development including hardware and software design. Though the data transmission rate is not as high as standard bluetooth , Bluetooth low energy technology in wearable healthcare systems is crucial in compressing the device volume and prolong the battery life.

REFERENCES

[1] A. Pantelopoulos and N. Bourbakis, "A survey on wearable sensor-based systems for health monitoring and prognosis," *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol. 40, no. 1, p. 1C12, Jan 2010.

[2] O. Mazhelis, E. Luoma, and H. Warma, "Defining an internet-of-things ecosystem," in *Internet of Things, Smart Spaces, and Next Generation Networking*. Springer, 2012, pp. 1–14.

[3] C. Gomez, J. Oller, and J. Paradells, "Overview and evaluation of bluetooth low energy: An emerging low-power wireless technology," *Sensors*, vol. 12, no. 9, pp. 11 734–11 753, 2012.

[4] S. Patel, H. Park, P. Bonato, L. Chan, and M. Rodgers, "A review of wearable sensors and systems with application in rehabilitation," *Journal of neuroengineering and rehabilitation*, vol. 9, no. 1, p. 21, 2012.

[5] T. Zhang, W. Tang, and E. S. Sazonov, "Classification of posture and activities by using decision trees," in *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE*. IEEE, 2012, pp. 4353–4356.

[6] T. Zhang, G. D. Fulk, W. Tang, and E. S. Sazonov, "Using decision trees to measure activities in people with stroke," in *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE*. IEEE, 2013, pp. 6337–6340.

[7] K. Morikawa, A. Matsumoto, S. Patki, B. Grundlehner, A. Verwegen, J. Xu, S. Mitra, and J. Fenders, "Compact wireless eeg system with active electrodes for daily healthcare monitoring," in *Consumer Electronics (ICCE), 2013 IEEE International Conference on*. IEEE, 2013, pp. 204–205.

[8] H. Wang, D. Peng, W. Wang, H. Sharif, H.-H. Chen, and A. Khoynezhad, "Resource-aware secure ecg healthcare monitoring through body sensor networks," *Wireless Communications, IEEE*, vol. 17, no. 1, pp. 12–19, 2010.

[9] A. M. Dixon, E. G. Allstot, D. Gangopadhyay, and D. J. Allstot, "Compressed sensing system considerations for ecg and emg wireless biosensors," *Biomedical Circuits and Systems, IEEE Transactions on*, vol. 6, no. 2, pp. 156–166, 2012.

[10] X. Xu and M. Zhong, "Wireless body sensor networks with cloud computing capability for pervasive healthcare: Research directions and possible solutions," in *Frontier and Future Development of Information Technology in Medicine and Education*. Springer, 2014, pp. 979–988.

[11] K. Pahlavan, *Principles of wireless networks: A unified approach*. John Wiley & Sons, Inc., 2011.

[12] A. C. W. Wong, M. Dawkins, G. Devita, N. Kasparidis, A. Katsiamis, O. King, F. Lauria, J. Schiff, and A. J. Burdett, "A 1 v 5 ma multimode ieee 802.15. 6/bluetooth low-energy wban transceiver for biotelemetry applications," *Solid-State Circuits, IEEE Journal of*, vol. 48, no. 1, pp. 186–198, 2013.

[13] M. Ali, L. Albasha, and H. Al-Nashash, "A bluetooth low energy implantable glucose monitoring system," in *Microwave Conference (EuMC), 2011 41st European*. IEEE, 2011, pp. 1265–1268.

[14] [Online]. Available: https://jawbone.com/up

[15] L. J. Mena, V. G. Felix, R. Ostos, J. A. Gonzalez, A. Cervantes, A. Ochoa, C. Ruiz, R. Ramos, and G. E. Maestre, "Mobile personal health system for ambulatory blood pressure monitoring," *Computational and Mathematical Methods in Medicine*, vol. 2013, p. e598196, May 2013.

[16] A. Dinh, Y. Choi, and S.-B. Ko, "A heart rate sensor based on seismocardiography for vital sign monitoring systems," in *Electrical and Computer Engineering (CCECE), 2011 24th Canadian Conference on*. IEEE, 2011, pp. 000 665–000 668.

[17] J. I. Wiegerinck, J. Boyd, J. C. Yoder, A. N. Abbey, J. A. Nunley, and R. M. Queen, "Differences in plantar loading between training shoes and racing flats at a self-selected running speed," *Gait & posture*, vol. 29, no. 3, pp. 514–519, 2009.

[18] H. Mamaghanian, N. Khaled, D. Atienza, and P. Vandergheynst, "Compressed sensing for real-time energy-efficient ecg compression on wireless body sensor nodes," *Biomedical Engineering, IEEE Transactions on*, vol. 58, no. 9, pp. 2456–2466, 2011.

[19] K. Ito, T. Nakayama, and T. Ukawa, "Pulse oximeter," Oct. 18 1994, uS Patent 5,355,882.

[20] E. Sammon, N. Hancock, N. Kennedy, and V. Pomeroy, "Characterising lower limb muscle activity and test-retest repeatability of emg measures in healthy adults during upright pedalling," *International Journal of Therapy And Rehabilitation*, vol. 21, no. Sup7, pp. S4–S5, 2014.