Imperial College London

Department of Electrical and Electronic Engineering

Final Year Project Report 2014

Project Title:	**A Wireless Low Energy Ambulatory Electroencephalogram**
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Abstract

Certain neurological medical disorders require continuous monitoring to fully understand and diagnose. Examples of medical interest include epilepsy, syncope, multiple sclerosis, migraines, strokes, Parkinsons and Alzheimers disease. Electroencephalography (EEG) is the recording of electrical activity along the scale, resulting from ionic current flows within the neurons of the brain and is useful for both diagnostic and monitoring such afromentioned conditions. Monitoring brain activity can help physicians understand certain characteristics, triggers, and the severity of the disorder. It may be possible to gauge the regions of the brain where the condition is originating from and if the patient is a suitable candidate for treatment.

However, patients are unlikely to suffer from neurological disorders while at the clinic as they often appear sporadically and with little to no warning. In such circumstances the patient could remain in hospital indefinitely, however seizures can be minutes to years apart, and sometimes are not realised or detected without proper equipment. Such circumstances lend themselves to an ambulatory system, where the patient can be monitored continuously without discomfort or hospitalisation, improving quality of life while decreasing costs.

With the emergence of low power wireless technologies coupled with portable devices such as tablets and phones, it is a natural technological step to bring care and monitoring out of the hospital and into the home. Through leveraging of low energy radio capable devices, i.e. smartphones and tablets, in the context of an ambulatory EEG, it is possible to empower the patient to inexpensively take health care into their own home and out of the hospital. Further, while this project is targeted at EEG signals, there is no reason why this research and technology cannot be applied to other signals and systems, examples including glucose monitoring, electrocardiography and spirometers.

[1]

Contents

1 Acknowledgements

The opporunity is taken here to express gratitude to all those who have directly contributed towards the project.

Firstly, the project surperivsors, James Mardell, Chen Guangwei and Esther Rodriguez-Villegas for their.

Cambridge Silicon Radio providing hardware and technical support. Employees particurarly are Adam Hill, Martin Spikings, Mark Wade, Neil Stewart and Simon. The recently launched uEnergy forum is an excellent source of . CSR also await a report on the speed of

Dr. Nissim Zur, CEO of Vitelix Limited is an expert in low power wireless technologies, and has conversed over many aspects of the final chip used. Further, has also taken an interest in this project's work in regards to maximising the speed, and has requested the results be shared with him.

Finally, and arguarbly most importantly Mike Harbour and Victor Boddy for their efforts in printed circuit board manufacture and assembly. Countless hours were spent in the lab pushing the department's PCB fabrication facilities outside their specifiction and to their limit.

2 Introduction

Patients, however, are unlikely to suffer from neurological disorder while at the clinic as they often appear sporadically during day to day life and with little to no warning. In such circumstances the patient could remain in hospital indefinitely, however seizures can be minutes to years apart, and sometimes are not realised or detected without proper equipment. Such circumstances lend themselves to an ambulatory system, where the patient can be monitored continuously without discomfort or hospitalisation, thus improving quality of life.

2.1 Problem Landscape and Motivation

Neurological disorders and their sequelae are currently estimated to affect upto one seventh of the world's population, a figure which currently stands at 1 billion. With the ever increasing life expectency and decreasing (relative) fertility rates, the population age demographic has shifted towards an ageing population. In tandem, the rates for neurological disorders has increased and is expected to increase further. Diagnosing, monitoring and treating many of these diseases is currently a costly procedure simply due to the time.

Unfortunately many neurlogical disorder symptons occur sporadically with little to no inidication of an event, such a in the cause of a seizure for epilepsy.

The vast majority of modern smart phones are now being equiped with Bluetooth Low Energy (BLE) or "Bluetooth Smart" technology. This is a relatively new technology design branded off the popular Bluetooth technology which gained popularity in the early part of last decade. While the two technologies share the same name, their design and operation is very much different. Although origianl Bluetooth's and BLE's use cases may overlap in some scenarios, they were designed to perform well under different circumstances.

By coupling cheap low power sensors and radios, with powerful ubiquitous consumer technology, it is possible not only to cheaply and efficiently monitor patients, improve the quality of life for patients but also help physicians further their understanding of neurological disorders.

Currently BLE is the only radio technology that is currently being built into all smart phones and tablet devices while offering power consumption low enough to enable a long lifetimes from a lightweight power source. In comparison classic Bluetooths power consumption is typically 1 to 2 orders of magnitude higher than BLE. Through leveraging widely popular and familiar smart phone devices with this new technology, in the context of an ambulatory EEG, it is possible to empower the patient to inexpensively take health care into their own home and out of the hospital.

2.2 Existing Technologies and Products

With the plethora of emerging low power wireless technologies coupled with portable devices such as tablets and phones, it is a natural technological step to bring care and monitoring out of the hospital and into the home. The consumer fitness sector is being targeted quite strongly, and many devices already exist that utilise lower power technologies to act as gateways for real-time data logging. For example, there already exists a competitive market between heartbeat monitors, cadence monitors and pedometers. These activity trackers use low power electronics and radios to log users activities and update the user in real time with activity information through the users phone or smart watch. Popular products on the market at the time of writing include the Fitbit, Fuelband and Jawbone, which all use the BLE technology to connect to smartphones.

2.3 Project End Goals

Originally the project was introduced as "Maximising Bluetooth Low Energy throughput of EEG signals", however

Currently, the Imperial College Circuit and System's group has a wired EEG measurement device. The wired connection between the EEG sensors and a computer cause patients to remain fairly immobile and hence are impracticable for long periods of use. This project will explore using BLE technology for electrocengraphy, and build a prototype system capabale of interfacing with an analouge front to transmit EEG data to a portable device such as a tablet or smart phone. The project will explore the maximum throughput of such a device along with its power consumption.

At the time of writing, the circuits and systems group at Imperial College have recently taped out a full custom silicon analouge front-end design for manufacture, however these chips will not be available for use before the project deadline.

Hard requirements of the project include

- Running time of atleast 12 hours
- Channel resolution of 8 bits (albeit number of channels undefined)
- A weight of less than 10 grams
- 10 meter range
- BLE wireless technology
- Ability to communicate with a smart phone or tablet

2.4 Structure

3 Theory and Technology

3.1 Bluetooth Low Energy

The original Bluetooth, hereforth refered to a Bluetooth Classic (BTC), was intially concieved as the solution to wired communication over short distances (typically less than 100m). The original specification had an air over-the-air rate of 1MBps, though this has increased to around 3 MBps in the latest version of BTC. Similarly, BLE has an over-the-air rate of 1MBps. Despite the odd realisation that BLE, a much newer technology, has the same over the air rate of last the first incarnation of BTC, the maximum theoretical throughput of BTC is 700kBps, compared to less than 250kBps for BLE - roughly one third of the maximum throughput BTC was capable of (the latest version of BTC brings the disparity to one ninth). While intuatively it may seem that BLE is a less efficient technology, BLE can be orders of magnitudes more efficient than BTC in particular use cases.

Applications where BLE excels in are ones where communication between two devices is only required intermitently, and the volume of information sent is small. An example would be a thermometer in a green house connected by radio to a visual display unit inside the home. Temperature changes at a rate slow enough that it is only necessary to check the temperature every 10 minutes. Once every 10 minutes the radio thermometer device can wake up take a measurement, send a notification of a measurement then return to a deep sleep. BLE does this much better than BTC, taking only a few milliseconds to connect. BTC takes between a few hundred milliseconds to several seconds to reconnect. While both millisecond orders of magnitude and second orders of magnitude are small when compared to an order of magnitude of minutes, over time it adds up to a significant amount, and BLE devices can last many years of a small, single coin cell. BLE is excellent for applications which involve small episodic transmission of data. In the scenario described a BTC system would have a lifetime of approximately 100 days from a typical 3v lithium cell. Off the same cell, a BLE system would have a lifetime of many years. In fact, in this scenario the BLE system lifetime can be extended further as BLE can support connectionless communication, whereby it simply wakes up and transmits the thermometer state to any device that's listening without the need for acknowledgement.

The reason the reconnection times are much faster for BLE is as far as the communication devices are concerned, they never disconnected. Rather in the BLE protocol, the devices agree to meet a specified periods known as connection interval (CI). The devices are free to perform any operations in the mean time, though typically enter a state of hibernation. In many scenarios between two radios, one device will be much more power conscious. In the example above, the battery powered device in the greenhouse would typically be the power conscious device while the visual disuplay unit inside the home will likely be powered from the grid, and have no concern as to its power consupmption. In these situations, we define the power conscious device to be the slave and the remaining device to be the master.

The slave device also has the ability to skip connection intervals. That is, the slave to skip a upto a predetermined number of connection intervals, known as the slave latency. While the master must always check back to see if the slave has sent anything, the slave, if it has nothing to send, doesn't need to wake up. For example, if the slave latency is 120, and the connection interval is 1000ms, then the slave is not obliged to communicate with the master for upto 2 minutes, despite the master having to check every 1000ms. If the slave is not able to make contact with the master after 2 minutes, then the master will begin counting the number of times the slave has missed the obliged connection period (that is the CI multiplied by the time slave latency). If this value reaches above a certain threshold (a typically recommened value of 6), the master will consider the slave disconnected, and be required to go through a connection process again[UNLESS USING BROADCASTING TO SEND DATA]. Continuing with the scenario, the slave will be considered disconnected if it hasn't made contact with the master after 12 minutes.

Another contribution to reduced power over BTC is the reduction in the number of channels used in communicaton. BTC, BLE along with other wireless technologies that operate in the 2.4GHz ISM band such as a WiFi and ZigBee all make use of spread spectrum techniques to achieve a sufficient level of noise immunity. That is, the available bandwidth is split (spread) into smaller channels and radios communicate between one another using a pre-dertmined channel hop sequence. As the number of channels decreases, the channel band size grows requiring less accurate and complex modulation hardware, hence decreasing power consumption. BTC originally used 79 channels, and BLE reduces this to 39.

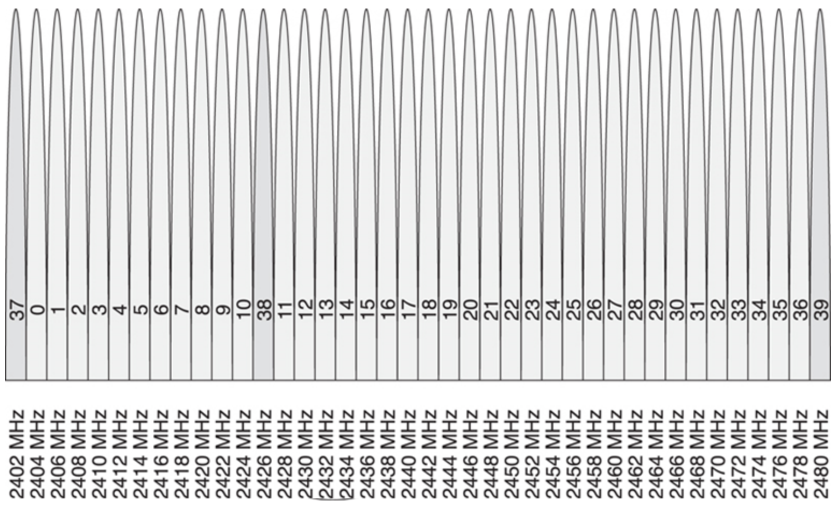

Figure 1: BLE channels (advertisement channels render darker)

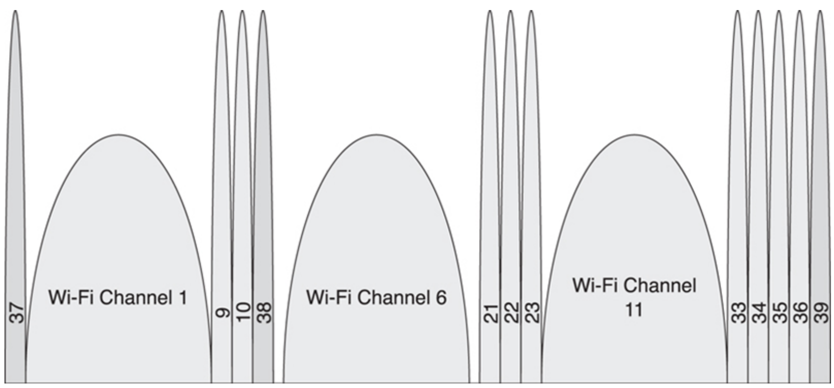

Figure 2: BLE channels with WiFi channels overlaid

The number of channels dedicated to advertising has also decreased, meaing less time is spent searching for discoverable devices. The advertisement channels have been specifically chosen not to interfere with the common WiFi channels. Finally, the radio characteristics are very dependent on temperature. Complex mechanisms are used to recalibrate on-the-fly radio parameters. Due to the episodic nature of BLE the radio does not come under such thermal extremes. All these design changes have positive hardware ramifications. The reduced compelxity of BLE means reduced hardware requirements (notably memory), in turn reducing the leakage current.

Bluetooth was designed with the idea that it would be used to do many common jobs, and hence particular configurations were built into it. In Bluetooth, these configurations are known as profiles. Example profiles include the audio distribution profile (A2DP), which is used in by many Bluetooth product manufacturers to allow a device, such as a phone to interact with an audio system, such as in a car. Another example would be the serial port profile (SPP), meant to emulate the highly popular and robust RS-232 (serial) standard for data transfer. This is all built into what is known as the Bluetooth stack a software framework that interacts between the physical layer and the application layer.

BLE borrows many of these concepts and features and it is often mistakenly thought of as BTC operating at lower speeds and power consumption. It is not currently compatible with Bluetooth and there are no plans for it to be. As mentioned, BLE has a maximum application throughput of roughly one third that of the BTC version 1.0. There are many reasons for this, but all ultimately converge on power. BLE was designed to be simple, with a 'less is more' approach and if things are simple they can be done using less hardware, and ultimately less power. Like BTC, the BLE architecture has 3 over-arching parts: Application, Host and Controller. The controller, simply put, is the radio and the application the use case, which could be a cadence monitor, thermometer or even an electroencephalogram. It is the host controller interface (HCI), commonly known as the stack that provides the necessary software to enable the application layer to communicate with the radio (see Figure 3).

In an attempt to be economical with time and space components of the stack deemed irrelevant will not be discussed further here. For example a description of the security manager is not relevant as this project is not concerned with sending data over encrypted links. Similarly, the Logical Link Control and Adaption Protocol, while used extenivesly in all radio communication will not be discussed in detail as it doesn't provide any insight into maximising throughput or minimising power.

BLE's profiles are all built ontop of from the Generic Attribute Prorfile (GATT), which in turn is built upon the Attribute Protocol (ATT), a protocol optimised to run on BLE devices. Like in Bluetooth there are profiles, but these profiles are on a much smaller scale. The profiles arn't complex enough to warrant tailoring a microchiptowards a particular profile, unlike BTC, whereby chips would be specifically designed to excel in one profile (i.e. A2DP). Popular examples of BLE profiles include the heart rate profile (HRP), health thermometer profile (HTP) and even a glucose profile (GLP) with room for many more to be incorporated into the core BLE specification.

In BLE and BTC, there certain states the device. The same abstract view can be applied to both technologies and is shown in Figure 3. Note that depending on the role of the device, the state moves right (master) or left (slave) from standby. It may appearing confusing to have another state for scanning which can only move into the standby state, but this is useful for searching and discovering devices with no commitment to connecting.

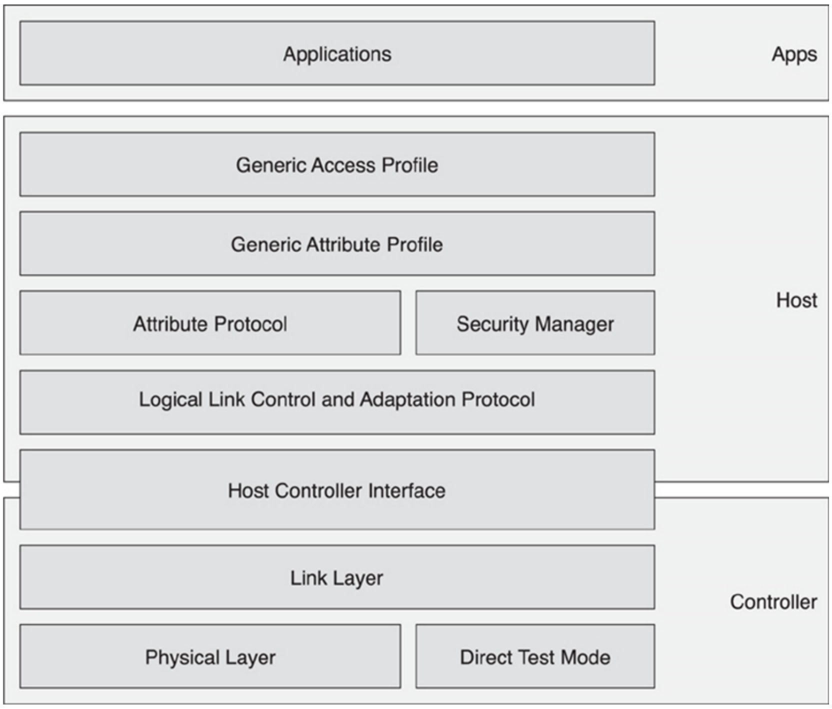

Figure 3: BLE Architecture

In classic Bluetooth there are 79 channels, all of which could be used to both transmit data and advertise. BLE uses only 40 channels, and segments 3 channels for advertisement and the remaining 37 channel for data. Figure 4 show this. By only have 3 channels, a BLE slave will only have to broadcast on these few channels (and equally the master will only have to listen on these 3), saving power while decreasing connection latency.

4 Preliminary Research

4.1 Radio Evaluation

5 Prototype Design

6 Results

7 Evaluation

7.1 Power Analysis

7.2 Bill of materials

8 Conclusions and Future Work

On the whole, the project has

Not all tablets will be able to run at full speed

Ideally, it is desirable to write a conference style paper.

Useful for CSR

9 Final Remarks

A vast array of technologies and tools were used throughout this project. Below highlights those that are non-trivial and were of significant importance

- Git verisioning control - For versioning and segmenting the workflow
- xIDE - CSRs integrated development suite for compiling and debugging CSR-stack based chips. This is where the firmware for the CSR1010 MCU was written
- Wireshark - Invaluable in analysing the packets and control flow between BLE radios, unfortunately must be used offline
- SmartRF online packet sniffer - Useful as a low-speed packet sniffer. Extremely useful in the early days of the project, however the throughputs eventually obtained rendered the tool and hardware redundant as it was not capable of such speeds
- Visual Studio 2013 - Primairly used for developing the tablet application. Highly useful for "knocking up" quick throughput expirements

The large amount of both written and generated code is to vast to warrant being included in this report. Therefore is has been decided to make it publically available online at the git repositry address `https://github.com/proftom/AmbulatoryEEG`.

10 Bibliography

References

[1] R. Quian; Rosso O. A.; Kochen S. Blanco S; Quiroga. *Time-frequency analysis of electroencephalogram series.* Tech. rep. 1995, pp. 1–3.

11 Appendix

11.1 Acronyms

EEG Electroencephalography

BLE Bluetooth Low Energy

BTC Bluetooth Classic

GATT Generic Attribute Prorfile

ATT Attribute Protocol

CI connection interval

12 User Guide