A WI-FI BASED SMART DATA LOGGER FOR CAPSULE ENDOSCOPY AND MEDICAL APPLICATIONS

A Thesis Submitted to the College of

Graduate Studies and Research

In Partial Fulfillment of the Requirements

For the Degree of Masters of Science

In the Department of Electrical and Computer Engineering

University of Saskatchewan, Saskatoon SK, Canada

By

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ABSTRACT

Wireless capsule endoscopy (WCE) is a non-invasive technology for capturing images of a human digestive system for medical diagnostics purpose. With WCE, the patient swallows a miniature capsule with camera, data processing unit, RF transmitter and batteries. The capsule captures and transmits images wirelessly from inside the human gastrointestinal (GI) tract. The external data logger worn by the patient stores the images and is later on transferred to a computer for presentation and image analysis.

In this research, we designed and built a Wi-Fi based, low cost, miniature, versatile wearable data logger. The data logger is used with Wi-Fi enabled smart devices, smart phones and data servers to store and present images captured by capsule. The proposed data logger is designed to work with wireless capsule endoscopy and other biosensors like- temperature and heart rate sensors. The data logger is small enough to carry and conduct daily activities, and the patient do not need to carry traditional bulky data recorder all the time during diagnosis. The doctors can remotely access data and analyze the images from capsule endoscopy using remote access feature of the data logger.

Smartphones and tablets have extensive processing power with expandable memory. This research exploits those capabilities to use with wireless capsule endoscopy and medical data logging applications. The application- specific data recorders are replaced by the proposed Wi-Fi data logger and smartphone. The data processing application is distributed on smart devices like smartphone /tablets and data logger. Once data are stored in smart devices, the data can be accessed remotely, distributed to the cloud and shared within networks to enable telemedicine. The data logger can work in both standalone and network mode. In the normal mode of the device, data logger stores medical data locally into a micro Secure Digital card for future download using the

universal serial bus to the computer. In network mode, the real-time data is streamed into a smartphone and tablet for further processing and storage.

The proposed Wi-Fi based data logger is prototyped in the lab and tested with the capsule hardware developed in our laboratory. The supporting Android app is also developed to collect data from the data logger and present the processed data to the viewer. The PC based software is also developed to access the data recorder and capture and download data from the data logger in real-time remotely. Both in vivo and ex vivo trials using live pig have been conducted to validate the performance of the proposed device.

ACKNOWLEDGMENTS

This research was supported by Natural Science and Engineering Research Council of Canada (NSERC). The equipment and lab infrastructure were supported by Canada Foundation for Innovation (CFI) and Western Economic Development (WED).

I would like to acknowledge my supervisor Dr. Khan Wahid without whom this research project would not have been possible. I am most grateful for his guidance, valuable advice and resources for this research. I would like to give thanks to lab peers Dr. Tareq Hasan Khan and Mohammad Shamim Imtiaz for their help and support during various experiments.

Finally, I am thankful to my parents, my child and especially my wife, Shriti Chitrakar for their support.

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LIST OF PUBLICATIONS

Following are the publications related to this work by the author:

Journals:

- Tareq H. Khan, Ravi Shrestha, Khan A. Wahid, and Paul Babyn, 2014, “Design of a Smart-device and FPGA based Wireless Capsule Endoscopic System”, Sensors & Actuators: A. Physical, Elsevier, vol. 221, pp. 77-87, doi: 10.1016/j.sna.2014.10.033.

Conference proceedings:

- Shrestha, R.; Khan, T.; Wahid, K., "A Wi-Fi adapter for medical data and imaging applications," in Energy Aware Computing Systems and Applications (ICEAC), 2013 4th Annual International Conference on, vol., no., pp.61-64, 16-18 Dec. 2013
  doi: 10.1109/ICEAC.2013.6737638
- Shrestha, R.; Khan, T.; Wahid, K., "Towards real-time remote diagnostics of capsule endoscopic images using Wi-Fi," in Biomedical Engineering (MECBME), 2014 Middle East Conference on, vol., no., pp.293-296, 17-20 Feb. 2014
  doi: 10.1109/MECBME.2014.6783262
- R. Shrestha and K. Wahid, 2014, “A Wi-F- based Personal Wireless Hub for Medical Data Acquisition Application”, Proceedings of the 37th Canadian Medical and Biological Engineering Conference (CMBEC), pp. 1-4

LIST OF ABBREVIATIONS

3G	Third Generation
AES	Advanced Encryption Standard
API	Application Protocol Interface
AP	Access Point
ARQ	Automatic Repeat Request
CPU	Central Processing Unit
DHCP	Dynamic Host Control Protocol
DMA	Direct Memory Access
ECG	Electrocardiograph
EEPROM	Electrical Erasable Programmable Read Only Memory
FIFO	First In First Out
FSM	Finite State Machine
GI	Gastrointestinal Tract
GPIO	General Purpose Input Output
GSR	Galvanic Skin Response
IC	Inter Integrated Circuit Communication
IRQ	Interrupt Request
LCD	Liquid Crystal Display
LED	Light Emitting Diode
PC	Personal Computer
PCB	Printed Circuit Board
RF	Radio Frequency
RX	Receive
SD	Secure Digital
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory
SSID	Service Set Identifier
TCP/IP	Transmission Control Protocol/ Internet Protocol
TX	Transmit
UART	Universal Asynchronous Receiver Transmitter
UDP	User Datagram Protocol
USB	Universal Serial Bus
WCE	Wireless Capsule Endoscopy
WEP	Wired Equivalent Privacy
Wi-Fi	Wireless Fidelity
WPA	Wi-Fi Protected Access
WPA2	Wi-Fi Protected Access II

CHAPTER 1

INTRODUCTION

1.1 Overview of Wireless Capsule Endoscopy System

The traditional wired endoscopy system consists of a flexible optical fiber with a miniature imaging device and a lighting apparatus at the top of the endoscopy tube. The wired endoscopy enables diagnosis of gastrointestinal (GI) tract related diseases, stomach pain, ulcers, gastritis, digestive tract bleeding, chronic constipation, polyps and colon cancer, and so forth [1]. The doctor can view the esophagus, stomach and upper part of the small intestine but, due to usage of a wired apparatus, the wired endoscopy system is unable to reach beyond the small intestine. Another procedure called colonoscopy enables examination of the colon but, most of the upper part of the colon is not accessible using a wired endoscopy. The discomfort and pain due to insertion of the endoscope and lack of complete GI tract visualization make wired endoscopy unpopular among patients.

The concept of a wireless capsule evolved from the development of an ingestible radio pill described more than 50 years ago [2]. The patient swallows a self-contained miniature electronic device with a temperature sensor which transmits temperature data using radio frequency. Later, a radio pill with a pressure sensor was explained in the literature [3]. The wireless capsule endoscopy has evolved towards smaller and miniature capsules because of the recent development of miniature electronics, low power circuits and fabrication technology.

In the wireless capsule endoscopy system, a patient swallows a small electronic pill with basically sensor, communication, processing, illumination and power system modules, as shown in the Figure 1-1. The types and numbers of sensors in a capsule depend on the capsule design and application. The image sensor is widely used for capsule endoscopy for capturing images inside the GI tract. The capsule with sensors like temperature, pressure, and pH is also available to diagnosis GI related diseases like congestion and gastric reflux and motility monitoring [5]. Once swallowed, the pill travels through the GI track and transmits images in real-time. The battery lasts from 4 to 8 hours [4-6] and it is sufficient for a one-time endoscopy diagnosis. The patient carries a data logger to save images transmitted by capsule. Patients will have limited mobility due to the antenna probes attached to the data recorder and the data recorder size. Even if patients are allowed to conduct their daily activities, the discomfort of carrying data logger and probes attached to the body limits the patient's ability to do extensive physical demanding activities. The pill is expelled from patient's body in a natural way (excretion), and there are very few cases where the pill is contained inside the body for a significant number of days. The images stored in data logger is then transferred to the computer and displayed on the workstation. The typical wireless capsule endoscopy system architecture shown in Figure 1-2 consists of implantable sensor, external data logger and data processing unit. A typical data processing unit is a computer or portable computer system with universal serial bus (USB) to download image data from the data logger. The commercial system also provides additional features of remote diagnosis through the internet and portable devices [6].

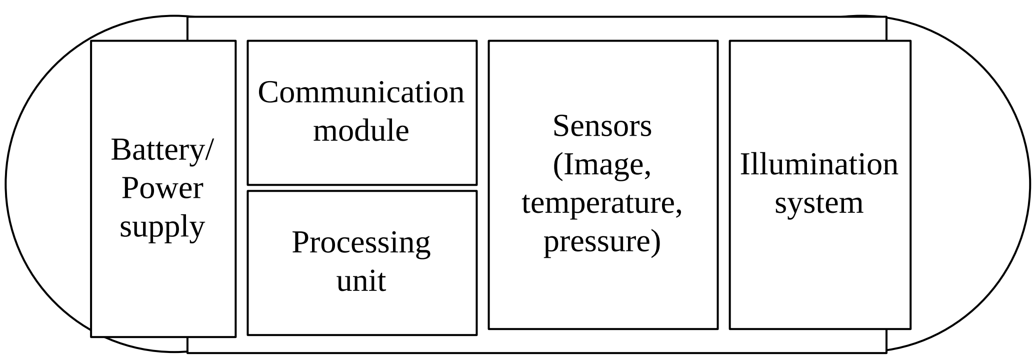


Figure 1-1. Basic modules inside the wireless endoscopic capsule.

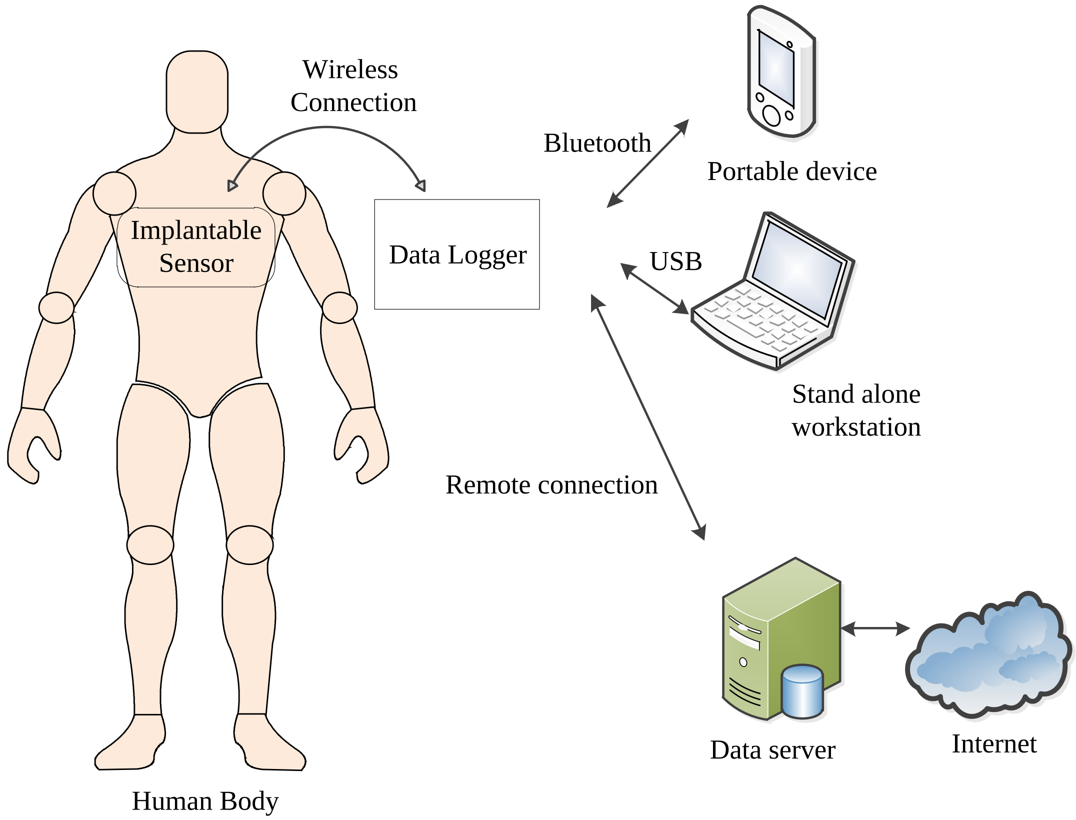


Figure 1-2. Typical system architecture of wireless capsule endoscopy system.

1.2 Research Motivation

Some commercial products are on the market for wireless capsule endoscopy system [4-6]. The commercial products are mainly proprietary data loggers and data protocols. The data loggers are bulky, costly and have limited capability regarding wireless capability and sensor interfaces. Our focus in this research is the design and development of a multipurpose Wi-Fi based data logger which can collect data from the wireless capsule and transmit to smart devices like computers, smartphones or similar devices with Wi-Fi connectivity. It will off-load the processing power and storage needed in the data logger. All data processing, image reconstruction and image storage are done in the smart devices. Smart devices like Android-based smartphones can be used as a data logger just by installing an “app”. It reduces the cost of buying dedicated data loggers for wireless capsule endoscopy-purpose. Porting of an “app” in “Apple” mobile platform is challenging and extensive software development task due to proprietary operating system. The proposed device is also self-contained system in which different types of medical sensors recording measures like, temperature and heart rate can be added. The proposed device allows the use of single data logger for different biosensors without using individual data loggers for each sensor. In this work, a prototype Wi-Fi based data logger unit and Android-based app is developed which is compatible with the wireless capsule developed in-house here at the University of Saskatchewan [7]. To validate the usability and evaluate performance, ex vivo and in vivo experiments are conducted in the animal intestine of a live pig.

1.3 Thesis Objective

The objective of this thesis is to develop a Wi-Fi based medical data logger and Android app for a wireless capsule endoscopy system. The following research objectives are set to meet our research goal:

- To design and develop a prototype Wi-Fi based medical data recorder with low power consumption and small size which can be easily worn by the patient without adding bulkiness.
- To develop firmware to support multiple interfaces to medical sensors.
- To develop an Android app for capsule endoscopy system with support for data logging, image reconstruction and presentation.
- To develop an Android app for supporting external sensors which measures temperature or heart rate.

- To evaluate the performance of data logger via in vivo and ex vivo experiments.

1.4 Thesis Organization

This thesis is organized into six chapters.

Chapter 1: *Introduction* presents the overview of capsule endoscopy system, the motivation of the research and the thesis organization.

Chapter 2: *Research Background* presents a discussion on commercial data loggers existing on the market and current research direction. This chapter also presents a related literature review on the data logger design.

Chapter 3: *Design of Data logger* presents a detailed design of the proposed Wi-Fi based data logger. The design specific requirements, hardware design, firmware structure is discussed in this chapter.

Chapter 4: *Android application* presents the architecture of Android application where the images are collected from the wireless capsule. The separate Android application is developed for data acquisition, data presentation and additional sensor support.

Chapter 5: *Experimental setup* presents all necessary experimental equipment for testing of the developed prototype, data formats and communication models.

Chapter 6: *Experimental Results* presents all results and experiments conducted with a pig's intestine using the developed prototype.

Chapter 7: *Summary and Conclusion* presents the overall summary and limitations of this research. This chapter also identifies possible future work related to this research.

CHAPTER 2
RESEARCH BACKGROUND

2.1 Introduction

The wireless capsule for endoscopy was approved by the United States Food and Drug Administration (FDA) in 2001 for visualization of abnormalities of the small intestine. Since then several commercial products emerged with innovative solutions to overcome limitations of current capsule endoscopy systems. Currently, three companies manufacture different models of endoscopy capsules approved by the FDA. They are PillCam [4] by Given Imaging Ltd out of Israel (acquired by Covidien in 2015), EndoCapsule [32] by Olympus America Inc., and MiroCam [6] by IntroMedic, Korea. The basic system architecture of all three commercial wireless capsule endoscopy systems is similar to the system diagram illustrated in Figure 1-2. The capsule endoscopy system consists of a wireless capsule endoscope, an array of antennas attached to the data recorder and a personal computer with proprietary software. Given Imaging have RAPID software to download images from the data recorder, exporting, tagging, marking and saving to external storages. Olympus has the WS-1 EndoCapsule with similar features of RAPID. All these products have a data recorder with internal storage media and display for real time viewing from the capsule. Some of the wireless capsule software are bundled with the workstation, that means the standalone software cannot be purchased separately [5]. All three commercial systems share the same architecture, yet they have different devices and software interfaces and are not compatible with each other. These capsule endoscopy systems have features of localization, automatic light control (ALC) or automatic brightness control (ABC), adaptive frame rate (AFR) and power savings. The Given Imaging and Olympus capsules communicates with data recorder using wireless interfaces and IntroMedic capsule communicates using human body communication.

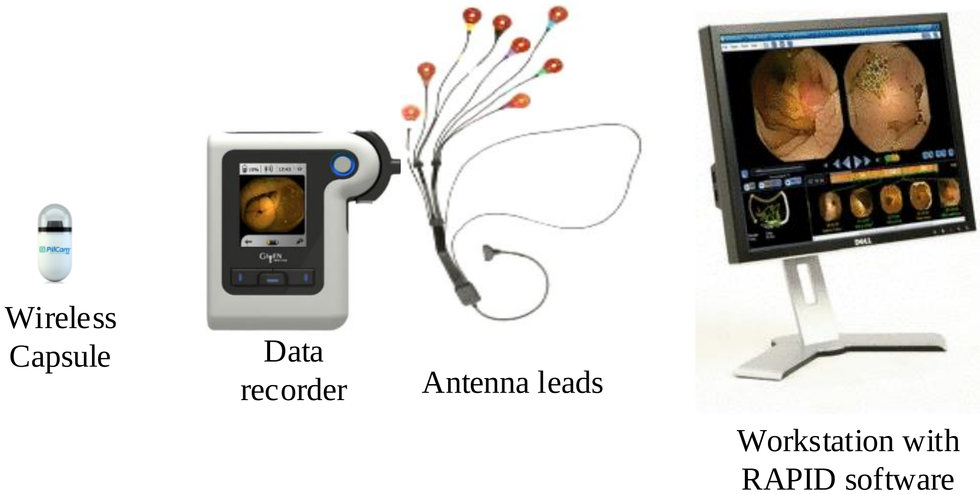
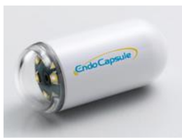


Figure 2-1. Given Imaging capsule endoscopy system with PillCam SB2 capsule.

Figure 2-1 shows the basic elements of capsule endoscopy system of Given Imaging. There are series of wireless capsules introduced by Given Imaging. PillCam SB series are used for small bowel imaging, PillCam COLON [4] is used for imaging the colon which has dual imagers for larger view area and PillCam ESO for imaging the esophagus. Besides capsules with image sensors, there are a series of wireless capsules equipped with temperature, pressure and pH sensors which are used for motility monitoring [5]. All these wireless capsules have common system architecture. Figure 2-2 shows the capsule endoscopy system from Olympus America. There is an additional device called Real-time viewer which enables physicians to check images from a capsule real-time. Figure 2-3 shows the IntroMedic wireless capsule endoscopy system which contains MiroCam capsules, MiroCam receiver with antenna leads and workstation software. There is no real-time viewer inbuilt in the receiver unit. The workstation software can be used as a real-time viewer for MiroCam capsules.

Besides these three leading companies, some wireless capsules are emerging from RF systems lab in Japan called Sayaka [49]. These capsules have advanced next-generation image processing and do not require an internal battery.



Wireless Capsule

Data recorder/ Real time viewer and Antenna leads

Workstation with ENDOCAPSULE 10 software

Figure 2-2. Olympus capsule endoscopy system with EndoCapsule.

MiroCam Wireless Capsule

Data recorder and Antenna leads

Workstation with MiroView software

Figure 2-3. IntroMedic capsule endoscopy system with MiroCam capsule.

The data recorder is one of the major components of the wireless capsule endoscopy system. The patient wears the data recorder during diagnosis. At the end of diagnosis, the data stored is transferred in the workstation via a USB interface. These data recorders are relatively bulky and restrict the mobility of patient during diagnosis. The comparison of the data recorders used in capsule endoscopy system is shown in the Table I. All three data recorders are comparable in size and weight. Regarding features, Given Imaging DR3 and Olympus data recorders have an inbuilt real-time viewer but the data recorder from MiroCam does not have a real-time viewer. The user needs to use PC software for real-time viewing for MiroCam devices. In this research, we propose the use of a smartphone and wireless data logger to replace these data recorders and PC software used for wireless capsule endoscopy application. The medical data recorders are discussed in Section 2.2.

Table I. Comparison of data recorders from Given Imaging [4], Olympus [32] and IntroMedic [6] for wireless capsule endoscopy system.

Data recorders	**Given Imaging (DR3)**	**Olympus**	**IntroMedic MiroCam**
Size (WxHxL) mm	85x130x37 mm	87x154x33 mm	85x140x40 mm
Weight (Inc. battery)	500g	390 g	350g
Battery	8800mAh	2860mAh	8800mAh
Real Time	Yes, inbuilt	Yes, inbuilt	Wire/ Wireless
Antenna	8 lead	5 lead	9 lead

2.2 Data loggers for medical application

Recent development of miniature circuits and advancement of wireless technology has attracted significant interest in the research area of wireless body network, medical data logger and data presentation. These portable medical devices fall into the category of wearable devices. Compact wearable devices are becoming popular and widely used for medical and recreational purposes. Several works have been reported in the field of data logging for medical application. Bio-sensors convert physiological signals like body temperature, respiratory [8], heartbeat [9-11], heart movement [12] [13] to electrical signals which are processed, transmitted and recorded in electronics device [14]. Raw or pre-processed data from biosensors is transmitted wirelessly or using wire to a data logger unit which can be recorded and utilized for the diagnostic purpose. Personal digital assistants have been utilized for monitoring vital physiological parameters like ECG signals using Bluetooth [15-17]. Various designs of medical data loggers are proposed in the literature. The work presented in [18] proposes the design of a microcontroller based data logger for medical application which contains a ECG electrode and analog front end circuits with additional accelerometers, a pressure sensor and a temperature sensor. The data from sensors are collected and stored in a 4 Mbit flash-memory and transferred to a computer using a serial cable. An ECG data logger is discussed in [19] where the data logger has a removable secure digital (SD) card for data storage. The data can be transferred to a computer using a serial RS232 interface. An ARM microcontroller is used in the design of a medical data logger which collects data from ECG electrodes and transmits data to a computer using Bluetooth technology [20].

Several data loggers are reported to sense fetal heartbeat [21], fetal movements [22], galvanic skin response (GSR) [14], sweat activity [23] [24] and human movement [25]. Most of the data loggers presented in the literature have wired connections with bio-sensors with data logging and processing unit inbuilt in the data logger. A custom designed medical data logger for individual application add cost and bulkiness to the user. Using several sensors for physiological monitoring adds to the complexity of data management and makes the user uncomfortable by the bulkiness of data recorders. The commercial companies came up with the idea of using personalized belts integrated with physiological sensors and a portable data logger [26] to address this issue.

Recent growth of smart devices also draws the attention of developers to develop health and fitness related application integrated into smartphones, tablets and portable devices. The

Android mobile platform is becoming popular for medical and wearable device software applications. There are several works reported based on an Android smartphone platform for medical data logging and presentation [53-58]. The work presented in [27] uses a Samsung's P1000 Galaxy tablet for processing analog data captured from developed hardware based on Xilinx XC3S1500FG320 FPGA, MSP430 microcontroller and TI ADS1258-EP analog-to-digital converter. The proposed hardware and software demonstrates the capability of processing medical data by commercial tablets with a comparison to a dedicated data acquisition platform from National Instruments (USB-6259 BNC DAQ).

Android wear [28] software platform of mobile devices are used for health and fitness tracking using physiological sensors. The data from sensors are directly logged and processed in the smart devices without the need of dedicated data loggers. The smartphone has been used in medical data logging and presentation in remote patient monitoring system by *MyFitnessCompanion* [17] which uses a smartphone as a data logger. This product uses Bluetooth sensors for monitoring body condition. It uses 3G or Wi-Fi to upload the measurements to *Microsoft HealthVault* to store and generate reports. The provided system needs an Android device for collection and uploading of data to a remote server. Bluetooth is used for uploading physiological data like blood pressure, heart beat rate, external body temperature to the data logger. These Bluetooth and Wi-Fi modules are not feasible for use in implantable devices (such as an endoscopy capsule or pacemaker) due to its power and size constraints. Low power and small size RF transceivers [29-30] are used in implantable devices to transfer data to an external data logger [31]. Most of the proposed medical data loggers are available to collect data from ECG [53], temperature, heartbeat [54], GSR and other biosensors, but there is no such device reported for use with the wireless endoscopic capsule. The traditional data loggers used for WCE are bulky, power consuming and have limited features for remote diagnosis functions. To address this problem, we propose a multi-purpose bridge device that collects data from implantable radio frequency (RF) or wired biosensors and re-transmits using a Wi-Fi network. The proposed system contains three key components: biosensor, data logging & processing unit. The biosensor is responsible for collecting data from physiological sensors. Some examples include ECG, body temperature, SCG, blood pressure or captured images from inside a human body via wireless capsule endoscopy. The proposed Wi-Fi based data logger acts as an intermediate device between biosensor and data processing unit. The biosensor measures physiological parameters and transmits it to the Wi-Fi data logger either by using radio frequency (RF) or a wired interface. The Wi-Fi data logger then either transfers data to the processing unit through Wi-Fi or can store locally into memory storage. The data processing unit may be a standalone workstation, simply a smartphone or a sophisticated data server. In this work, an Android mobile app is developed for wireless capsule endoscopy application.

The advantages of the proposed system are:

- *Portability:* Proposed Wi-Fi based data logger is a portable, smart and low power device.
- *Data logging in the smart device:* Any smart device with the Android operating system can be used as data logger just by installing the data logger app. The user can copy logged data from smartphone to a personal computer by using Bluetooth, USB or use cloud applications like Dropbox to share the logged data.
- *Real-time diagnostic:* Doctor can perform real-time diagnosis using developed software.

- *Remote diagnostic:* The proposed device can upload data to a remote server without the use of smartphone. The device can connect to Wi-Fi network and communicate with remote server for storing medical data. The medical data like images from wireless capsule can be used for remotely diagnosis.
- *Sensor interfaces:* It supports both wireless and wired biosensors. In this study, we used wireless capsule endoscopy developed in our laboratory as a wireless sensor.
- *Support for data intensive application:* The proposed system is based on high bandwidth data communication, which supports real-time image transfer like wireless capsule endoscopy.

CHAPTER 3

DESIGN OF DATA LOGGER

3.1 Introduction

The electronic capsule enables examination of the gastrointestinal tract (GI) where conventional wired endoscopy cannot reach. The commercial companies Given Imaging [4], IntroMedic [6], and Olympus [32] produces wireless capsule endoscopy system with different sensors and features. Most of the wireless capsule design use a camera as a primary sensor to capture images from the GI tract. The wireless capsule with pH, temperature and piezo resistive strain gauge pressure sensors is also commercially available for medical application. These capsules are battery powered and activated using either a magnetic switch or using a specially designed activation fixture. An activation fixture is a device with a magnet aligned to turn ON/OFF the reed switch inside the capsule. Only SmartPill [5] uses activation fixture to enable capsule power supply. Once activated, the capsule is swallowed by a patient with water to reduce discomfort caused by capsule. The capsule travels through the GI tract naturally. During its travel, the GI tract is illuminated via white light emitting diodes (LEDs) and the image sensor captures images at a predefined rate or adaptive frame rate. The captured images are transmitted using wireless communication or body communication method. In body communication method, the capsules use the human body as a conductive medium for data transmission to the electrodes attached to the body [61]. The captured image is stored in the data logger and later downloaded to the computer using universal serial bus (USB). The work presented in [31] presents Bluetooth and offline SD card methods for transferring data from the data logger to a computer. The system architecture of wireless capsule endoscopy system comes with various configurations. The minimal system consists of wireless capsule, external data logger and the data processing system.

In this chapter, the design of a portable data logger is discussed. The data logger hardware is designed via a compact printed circuit board (PCB) which stacks on the wireless transceiver module. The self-contained data logger can be used with other analog and digital biosensors.

3.2 Design requirements of the data logger

To realize the proposed data logger for capsule endoscopy system, the following design requirements were set:

- The data logger should be able to communicate with the wireless capsule in real time. The data logger should be able to accept commands from the smart host device and send that command to the capsule. The data logger should be able to receive data from the capsule and transmits to a smart device simultaneously.
- Several studies have been conducted to investigate transit time of the wireless capsule. The study [62] showed the small bowel average transit time of 4.3 hours. The study [63] showed the small bowel average transit time of 2-6 hours and large bowel transit time of 10-59 hour. The normal capsule endoscopy diagnosis lasts for 8 hours [64]. This suggests that the proposed data logger should operate at least 8 hours on battery power.
- The data logger should have enough memory to store data temporarily during transmitting and receiving data.
- The data logger should have analog inputs to accept data from analog sensors and digital ports (like UART, I2C) to communicate with external sensors.
- The data logger should be able to handle data communication with any data loss.
- The data logger should be easily configurable using smart host device.

3.3 Choice of wireless technology

Wireless technology has been widely used in medical devices [15-17] [29-30]. The evolution of different wireless technologies from short range body communication to long range Wi-Fi led the integration of wireless capability on medical devices. Table II shows a brief comparison of widely used wireless technology used in portable devices. ZigBee, Bluetooth, Bluetooth Low Energy, Body Communication, near field communication and radio frequency identification (RFID) are short distance wireless communication technologies. Bluetooth and Bluetooth low energy are popular in low power and low data rate applications like heart beat monitors, peripheral capillary oxygen saturation (SpO2) sensors and fitness tracking devices. These low power, low data rate wireless technology cannot be used in wireless capsule endoscopy due to the requirement of the high data rate for image and video transmission from the capsule to the data logger. The ZigBee and RFID are not popular in medical devices due to their extremely low data rate (128kpbs to 250kbps). Body communication technology has been used in capsule endoscopy with proprietary transceivers [6]. Wi-Fi is a popular wireless technology and widely used in public places, hospitals, and residences to interconnect Wi-Fi compatible devices to share information on internet or intranet. Wi-Fi is becoming popular due to its high bandwidth, moderate power consumption, long range, security and ease of use. Compared to other wireless technologies, Wi-Fi is becoming standard for internet communication in public and private places. This attracts medical devices to use Wi-Fi to connect local and remote devices within or outside of the corporate environment. In the proposed portable data logger for wireless capsule endoscopy, Wi-Fi is chosen due to following reasons:

i) *Compatibility:* Almost all smart devices (e.g., smartphones, tablets) are equipped with Wi-Fi devices which can communicate with other Wi-Fi enabled devices or Wi-Fi infrastructure. Since we are interested in using existing smartphones-tablets for data storage and processing, we have a choice of using either Wi-Fi or Bluetooth to communicate with a data logger.

ii) *Data rate*: The latest Wi-Fi standard 802.11ac supports a maximum data rate up to 600Mbps. This data rate is sufficient for real-time streaming of video and images from the wireless capsule to the data logger.

iii) *Range:* Wi-Fi data communication distance ranges from 10m to 100m according to the working environment. This distance is suitable for the purpose of wireless data logging from the capsule to a smartphone.

iv) *Versatile:* Wi-Fi wireless can be used in portable devices, data servers, data processing units, personal computers, handheld devices and can be easily integrated into computer networks. Due to flexibility and availability of wireless technology, it is widely used in private and public networks.

Table II. Comparison of different wireless technologies

	Data rate(bps)	**Range (m)**	**Power supply**	**Max node**	**Security**
ZigBee [42]	250k	10-300	1mW	65000	AES-128
Bluetooth [43]	3M	10	50mW-100mW	8	64/128-bits
BLE[44]	1M	10	0.01-0.5mW	8	128-AES
Wi-Fi[45]	>11M	10-100	3mW-6mW	32	128-AES
Bodycom [46]	<10k	Body to body	(3.6*10-2)mW	2	128-AES
NFC [47]	<0.2m	<15cm	less	Point to point	No
RFID [48]	128k	2m-10m	No battery need	64 bit - 1 Kbit	No

3.4 The data logger architecture

The basic architecture of the data logger is shown in Figure 3-1. The data logger is designed with a modular approach to ease modification in the future according to the specific data logging application. The data logger design contains five layers. The user input data flows from application (user space) to hardware layer. Data communication between each layers are bidirectional. Each layer is responsible for single task and transfers data from corresponding neighbor layers. Each layer of the data logger is explained in the following subsections.

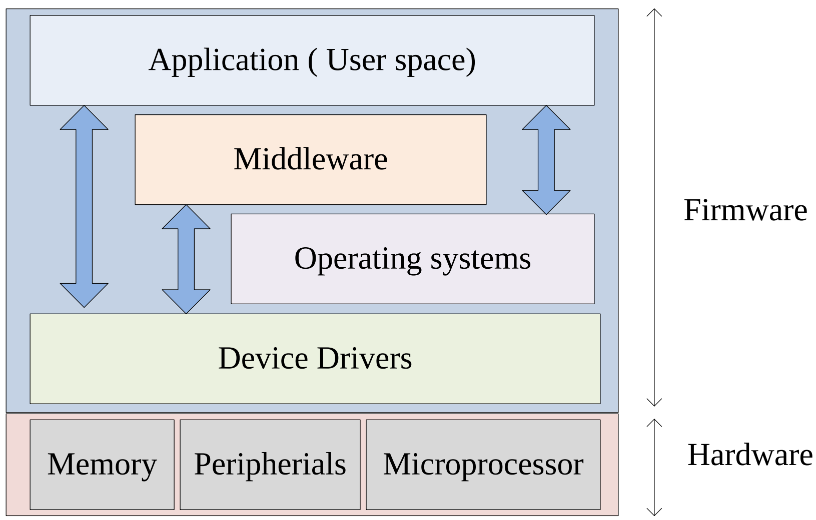


Figure 3-1. Basic architecture of proposed data logger.

3.4.1 Hardware

The hardware layer is the lowest layer in the design. Hardware components including a microprocessor, peripherals (data converters, power supply regulators, reset circuits and supporting electronics) and memory devices. Each hardware component is chosen precisely to meet the design requirements of low power consumption and small footprint. The design consists of a microcontroller, Nordic nRF24L01 RF transceiver [29], Texas Instruments CC3000 Wi-Fi module [33], 1Mb random access memory (RAM), microSD card interface, external interfaces, and a power supply unit. The overall block diagram of the hardware of the proposed data logger is shown in Figure 3-2.

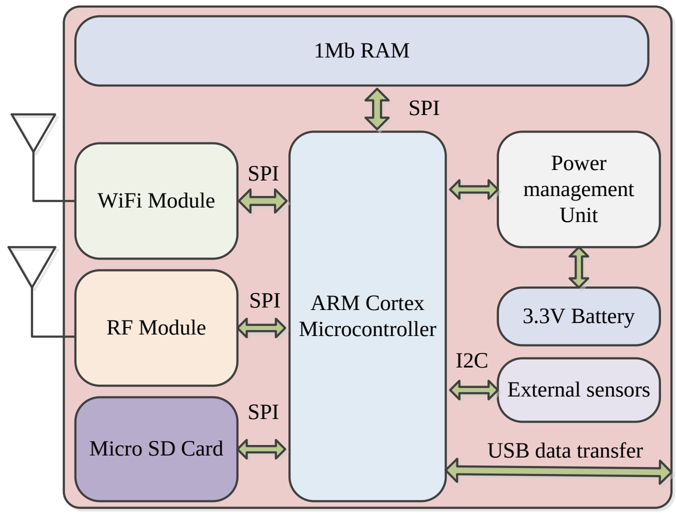


Figure 3-2. Overall block diagram for the proposed Wi-Fi based data logger.

3.4.1.1 Microcontroller

A low-power ARM Cortex-M4 microcontroller LM4F120 [34] from Texas Instruments is chosen for this design due to its adequate processing speed, the availability of peripherals like SPI, I2C, UART, direct memory access (DMA) and analog-to-digital converters. The microcontroller runs at 80MHz clock with 3 stage of sleep features to save power consumption. The microcontroller provides sleep, deep-sleep and hibernate modes to save power when minimal functionality is required. In the hibernate mode, power to the entire chip is turned off except to the 32KHz oscillator circuit, real time clock module, a battery monitor circuit and SRAM backup battery module. The microcontroller can be awakened from hibernate state using external interrupt signal. In sleep mode, system clock runs at 16MHz, central processing unit is running. In deep-sleep mode, the system clock runs at 30KHz to reduce deep-sleep mode current. The microcontroller has 256kB of flash memory to store the program, 8kB of SRAM and uses an internal oscillator for the system clock. The microcontroller is responsible for collecting, buffering, and transferring data from related interfaces according to the programmed mode. It controls all activities related to the data logger, RF transmitter, Wi-Fi data transmission and generates a control signal for overall management. All SPI communications are implemented through direct memory access (DMA) that increases the overall speed of data transfer from peripheral to the microcontroller, and vice versa.

3.4.1.2 RF transceiver

A Nordic RF transceiver (nRF24L01) module was chosen to make communication possible with the electronic capsule. The electronics capsule used in the wireless capsule endoscopy system proposed in [7] also uses a Nordic RF transceiver for data communication. The nRF24L01 supports a data rate up to 2Mbps over the air and provides an error checking mechanism for error free communication between transceivers. It guarantees the reception of data packet to the receiver by requesting an acknowledgment packet from the receiver to the transmitter. This is an essential requirement for communication between capsule and data logger as loss of a single packet can create a problem during data decoding in the data logger. A schematic of the RF transceiver and the microcontroller is shown in Figure 3-3. It is interfaced with the host microcontroller using an SPI interface at 8 MHz speed. SPI interface requires master in slave out (MISO), master out slave in (MISO), clock (SCK), and chip select (CSN). Beside these four signals, nRF24L01 requires two additional signals: interrupt request (IRQ) and chip enable (CE). RF transciever pulls IRQ signal logic high when it receives data or completes transmission. The host microcontroller uses IRQ signal to initiate data read/write oeration in RF transciever FIFO memory. The IRQ signal is also used in host microcontroller to awake host from its power saving modes. The CE signal is used to enable and disable RF transciever. The logic high in CE enables

RF transciever and logic logic disables the RF transciever. The host disables RF transciever to save power when RF transciever is not in use.

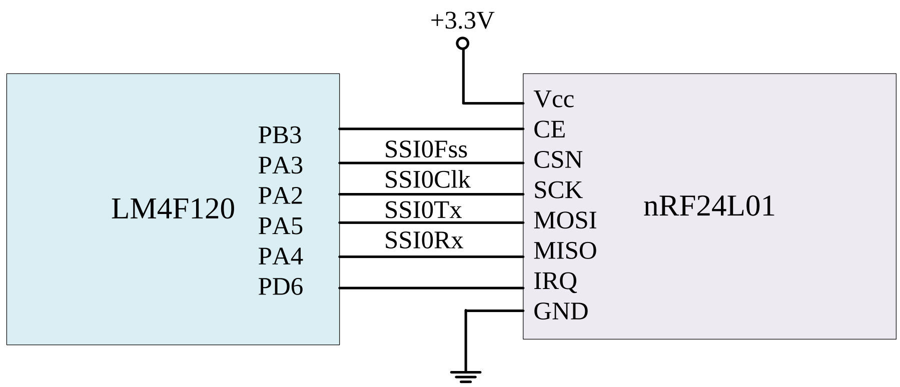


Figure 3-3. Interface between microcontroller and nRF24L01 RF transceiver.

3.4.1.3 Wi-Fi module

A TI CC3000 Wi-Fi module from Texas Instruments is utilized in this design to add Wi-Fi interface to the data logger. It is a self-contained wireless network processor operating on IEEE 802.11b/g standard. This module has an inbuilt embedded IPv4 TCP/IP stack. It consumes 207 mA at 3.3V supply during transmission and 103 mA at 3.3 V supply during reception on 802.11g mode. It is configured by smartphone using the Smart Config application which avoids additional user input interface in the data logger for configuring Wi-Fi connection related parameters like AP name, passcode and IP addresses. Texas Instruments provide the hardware abstraction layer (HAL) software without technical support. The HAL code was written in C programming langauge and Code composer studio version 6.9 software was used to compiling the project. The HAL code is then customized to satisfy our requirements. The unnecessary codes were removed from HAL. The CC3000 module is connected to the microcontroller using a serial peripheral interface (SPI) running at 20MHz as shown in figure 3-4. Additional pins for interrupt request is used to enable data transfer. The data transfer between Wi-Fi module and microcontroller is handled via DMA.

DMA takes over central processing unit for data communiation task. As data is avaiable for transmission, DMA handles start, stop and memory management without use of central processing unit. This allows central processing unit to involve in other system tasks instead of data communication.

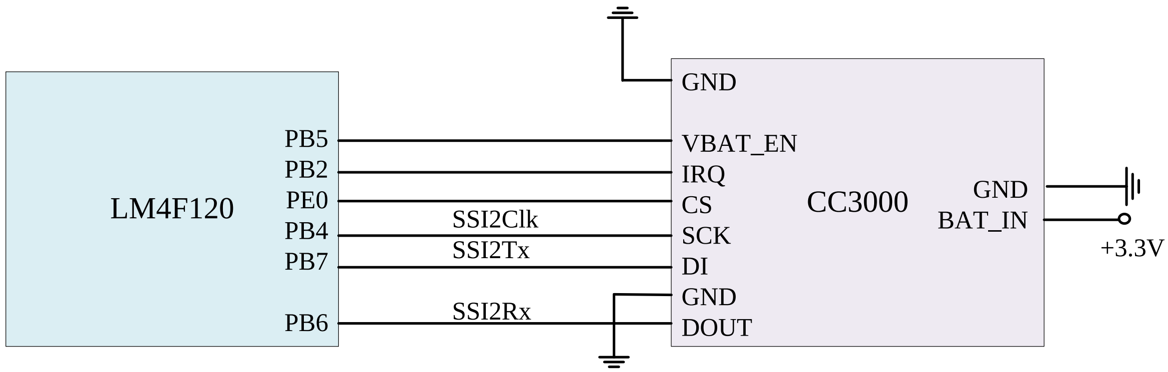


Figure 3-4. Interface between microcontroller and the CC3000 Wi-Fi module.

3.4.1.4 MicroSD card

The data logger is designed to work offline without using Wi-Fi connectivity. Data can be saved to a microSD card and later downloaded to the computer using microSD card reader. The microSD card is connected with the MCU using hardware SPI operating at 16 MHz clock speed. In the case of interruption in Wi-Fi network, there is chance of data beign lost. To avoid this issue, the firmware uses microSD card to save data temporarily until Wi-Fi network conenction is restored. Once the communication with smart device via Wi-Fi is resumed, data from microSD card is transferred to smart device. The data logger can support a maximum 4GB microSD card when the FAT32 filesystem is used to save data. The maximum memory required to save images from wireless capsule can be calculated using following equation:

$$X_{Bytes} = \left(\frac{l \times h \times b}{8}\right) \times f \times 3600 \times t$$

Where X_{bytes} = Total number of bytes required

l = width of an image in pixels

h = height of an image in pixels

b = number of bits per pixel

f = image acquisition per second (frames per second)

t = total image acquisition in hour

Considering image size of 160x120 pixels and bitmap format (24 bits per pixel), 2 frame per second and total image acquisition of 8 hour, the total number of bytes collected is:

$$X_{Bytes} = \left(\frac{160 \times 120 \times 24}{8}\right) \times 2 \times 3600 \times 8 = 3.31 \times 10^9\ Bytes = 3.31\ GBytes$$

This shows, 4GBytes of microSD card is sufficient for storing images images from wireless capsule capturing bitmap images of 160x120 pixels at the rate of 2 frame per second for 8 hours. Above calculation does not consider image compression. In wireless capsule endoscopy, images are compressed [37] due to limitation of bandwidth in RF transmission.

3.4.1.5 External interfaces

The data logger design is capable of interfacing other biosensors using analog and digital interfaces. An inbuilt 13-bit ADC can be used to digitized analog signals at a rate of 1MSps. Analog signals with a maximum signal amplitude of 3.3V are acceptable for data conversion. External digital interfaces like universal asynchronous receiver and transmitter (UART) and I2C are also available for future expansion. The dedicated UART port is also available for debugging data logger firmware.

3.4.1.6 Power supply

The data logger is designed to operate by one rechargeable 3.7V, 850mAh [35] polymer lithium-ion battery or micro USB power supply. When battery and USB are both connected, the battery continues to recharge until it is full. It takes 5 hours to fully charge the battery. When the battery is fully charged the charge controller stops current following to the battery. The battery charging circuit is shown in Figure 3-5. The MCP73831 [65] battery management controller uses constant-current/ constant-voltage algorithm to charge lithium-ion battery. The charging current is limited by the 2K Ohm resistor in PROG terminal of the battery charger. The charging current is limited to 505mA [65] which is rated maximum current supply of USB 2.0 interface [68]. The charging current is limited to the USB current supply limitation to avoid damage on the USB charging port. The battery charging circuit is responsible for monitoring battery charge level and charging condition. The battery charge controller provides status pin to indicate battery charging progress. A LED is connected to the status pin which glows to indicate the completion of battery charging. The data logger is operated by the battery when disconnected from the external power source.

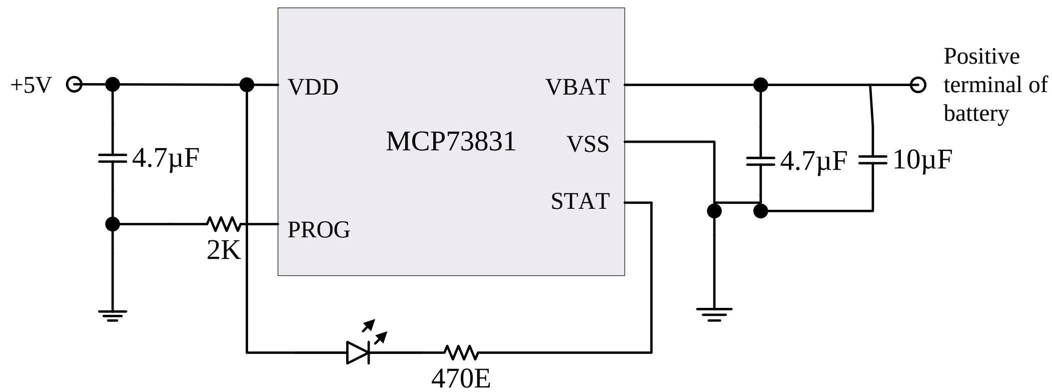


Figure 3-5. Power supply and battery charging circuit.

3.4.2 Firmware

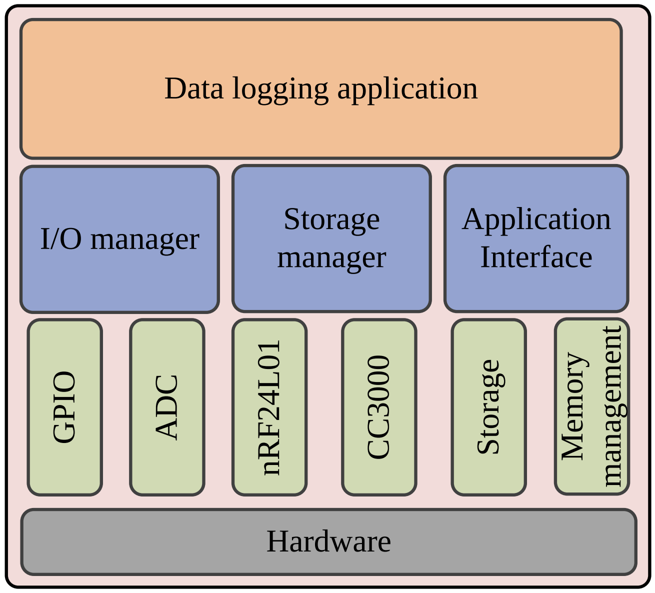


Figure 3-6. Firmware layers of the Wi-Fi data logger.

Figure 3-6 illustrates the firmware architecture for the Wi-Fi data logger. Each layer of the firmware is modularized so that future updates can be incorporated without making significant changes in the firmware. Texas Instruments provide low-level drivers in the form of application protocol interface (API). The device drivers for Wi-Fi, Nordic RF module and external interfaces are written in a modular fashion. The GPIO driver is responsible for handling low-level functions connected to GPIO pins like external switches and LEDS. The ADC driver handles initialization, configuration and controlling ADC functions. The storage driver handles tasks related to micro SD for saving offline data. Similarly, memory management device drivers monitor the activity in the buffers and protects memory from overwriting and overflows. On the top of low-level drivers, there are three middlewares: I/O manager, storage manager and application interface. I/O manager manages the I/O resources which includes all external interfaces connected to the Wi-Fi data logger. The Storage Manager handles the file system to save data onto the microSD card. The application interface provides configuration of devices and interfaces with the data logging application to low-level device drivers. Data collected from each interface is saved in the memory buffer. The core application layer is responsible for the processing of the data stored in the memory buffer. It handles the message from remote configuration application to configure Wi-Fi setting. In our implementation, Wi-Fi data is packetized into a group of 32 bytes to make it compatible with the data packet size of wireless capsule RF interface. Each packet in Wi-Fi interface consists of 32 bytes of data encapsulated in TCP/IP header. To make synchronous receive and transmit operation, we use same data packet structure with both Nordic RF transceiver and Wi-Fi transceiver. As stated earlier, Wi-Fi data logger can be used in other medical data logging applications, so firmware can be easily customized to adopt custom data packet structure according to the requirement of the application.

The data logger uses first in first out (FIFO) memory structure to store data in its random access memory during data communication between RF transciever and Wi-Fi module. The Wi-Fi data logger uses 768 bytes of the data buffer. The size of the data buffer is limited by the available random access memory (RAM) in the microcontroller. There is a provision for storing 1 Mbit of data in the external memory also. Considering the wireless capsule transmitting image of 160x120 pixels, 24 bits per pixel format, without using image compression technique, an image needs 57 Kbytes of memory space. Using 1Mbit (125Kbytes), two images can be stored in 1Mbit RAM before it is transferred via Wi-Fi interface. Since wireless capsule is transmitting images at 2 frames per second, The buffer memory can hold image data for 1 second, which is more than adequate for buffering purpose. In real world situation, the data logger does not use this buffer memory at all, because the Wi-Fi interface has bandwidth of 10Mb/s and the incoing data rate from Nordic nRF transciever is only 2 Mb/s. It avoids possibility of data congestion in Wi-Fi interface.

3.4.2.1 Firmware state machine

The firmware of the Wi-Fi data logger is designed based on a state machine as shown in Figure 3-7. Each state machine can change its state according to the value of state variable. Once the Wi-Fi data logger gets powered up, initialization of CPU takes place. The initialization state includes the following tasks:

a. Initialization of PLL for 50MHz CPU clock
b. Initialization of GPIO, I2C and SPI interfaces
c. Initialization of power mode, timer and software variables

Once CPU is initialized, the state machine goes to RF transceiver initialization state. This includes initialization of RF transceiver with default parameters as shown below:

Table III. Initial configuration parameters of Nordic nRF24L01 transceiver

S.No.	RF parameters	Initialization value
1.	Operating frequency	2.4GHz
2.	Transceiver mode	Recieve
3.	Automatic Repeat Request (ARQ)	Enable
4.	Transciever identification code	0xE7,0xE7,0xE7
5.	Data packet length	32 Bytes
6.	RF channel	100

Enabling transceiver into receive mode enables the Wi-Fi data logger to wait for a command from the computer. The automatic repeat request (ARQ) is an important parameter as it will guarantee error-free data transmission between two transceivers. The RF transciever uses cyclic redundancy check (CRC) to validate received data. If CRC fails, the reciever sends ARQ to the transmitter requesting resending the failed data packet. If After this state, the Wi-Fi adapter can go into either configuration mode or operating mode. This depends on the state of the external switch. If the Wi-Fi adapter is run for the first time, then it is necessary to setup the device with proper IP settings. When the switch is in configuration mode, the state machine goes into Smart Config mode where the user can setup the Wi-Fi adapter with Wi-Fi related settings like SSID, network password, and DHCP mode. After setup is finished, the Wi-Fi data logger goes into connection mode. It waits for the clients to be connected with hardware. The software is designed so that the Wi-Fi adapter acts as a server and other connecting devices acts as clients. Once clients are connected, each client is assigned a unique IP address. This completes the connection state. Once the connection is established, the device can handle two-way communication between the client and server. The state of communication is driven from IRQ so that the micro controller multiplex the RF and Wi-Fi data communication processes to share same processing resources.

Table IV. Initial configuration parameters of TI CC3000 Wi-Fi transceiver

S.No.	RF parameters	Initialization value
1.	Operating frequency	2.4GHz, IEEE 802.11 b/g
2.	Transceiver mode	Idle, listening
3.	Configuration mode	Depends on the state of external switch
4.	Default AP to connect	WCE_HUB
5.	Default IP address	192.168.0.100
6.	Default port number	34561

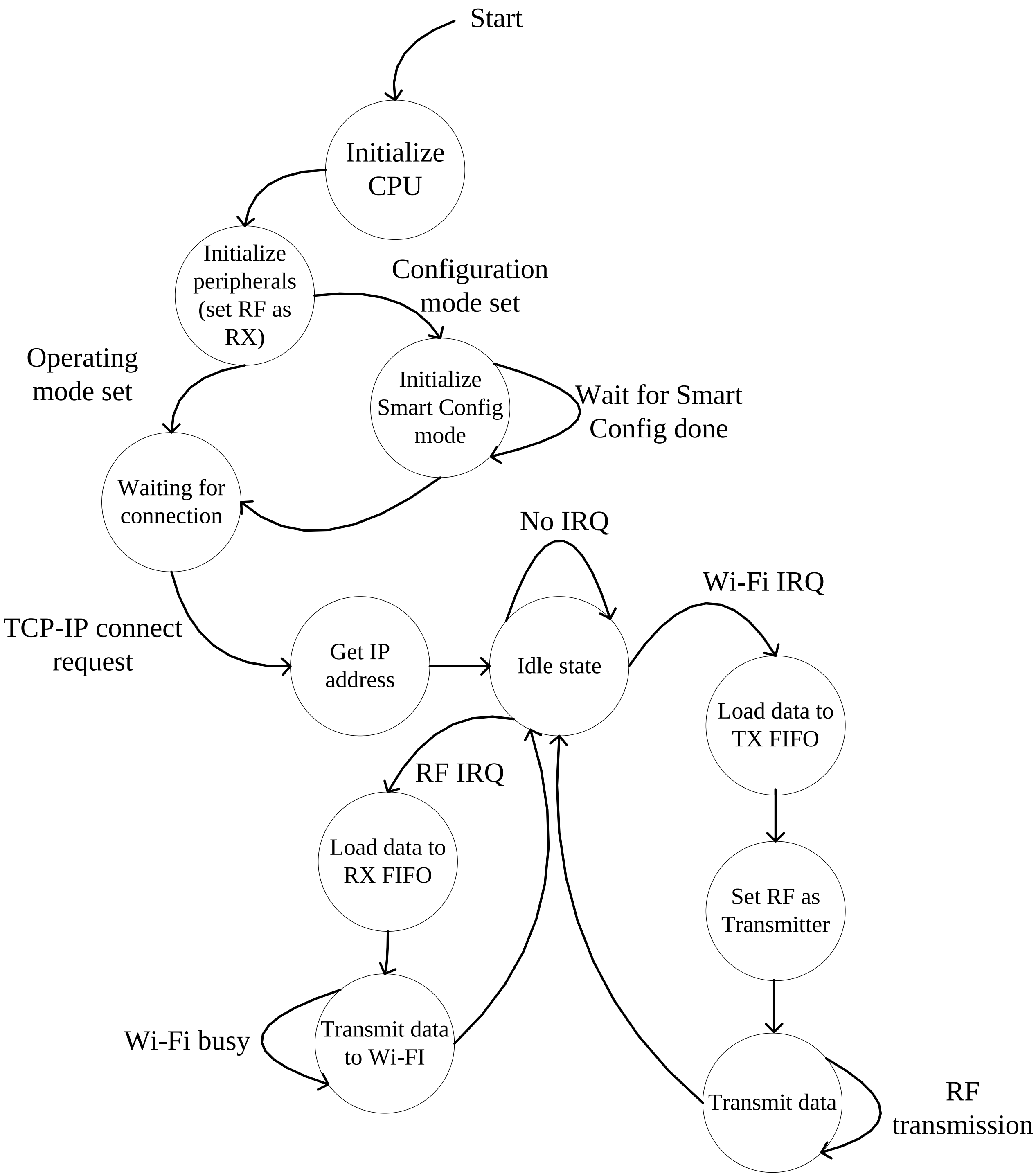


Figure 3-7. Finite state machine inside data logger firmware.

3.4.2.2 Memory buffer design

The cyclic buffer is designed to store data from Wi-Fi and RF interfaces temporarily. The buffer is 762 bytes which is enough to store a compressed image when used in the capsule endoscopy system. The structure of FIFO is shown in Figure 3-8. The memory is designed such that there will be overwritten protection and memory overflow protection. There are two pointers: read and write. When FIFO is empty, both read and write pointers will hold the same value. The difference between write and read pointer value gives the total number of bytes available in FIFO. Once data is read, the read pointer get increased by one byte and when a new byte is written the write pointer get increased by one. The pointers are implemented by using two counters. The counters keep tracks the position of both pointers. In the case where write pointer value is at its max (i.e., 768) and read pointer is at its initial position (i.e., zero) indicating there is no read activity, the FIFO stops loading data into the buffer to protect data override.

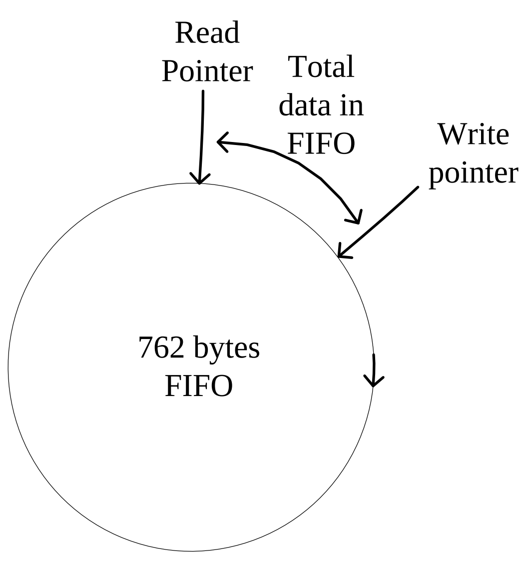


Figure 3-8. Cyclic ring buffer for buffering data.

3.4.2.3 Data logger configuration

The first step of using Wi-Fi enabled device os to configure it to a user's Wi-Fi network setting. The basic information needed for setup is AP name or SSID, security passcode if the network is secured using WEP/WPA/WPA2. The challenge of configuring Wi-Fi device is to have some user interface like LCD, touchscreen, keyboard to setup these parameters. However, the Wi-Fi data logger is small in size, and there is no LCD or user interactive device to give user input. To solve this problem, we used Texas Instruments Smart Config [36] for configuring the Wi-Fi device. This enables users to configure the Wi-Fi adapter without using any user input devices. The user can install the Smart Config app on any device connected to a host network and use the app to configure the Wi-Fi Adapter. The basic principle of Smart Config is shown below:

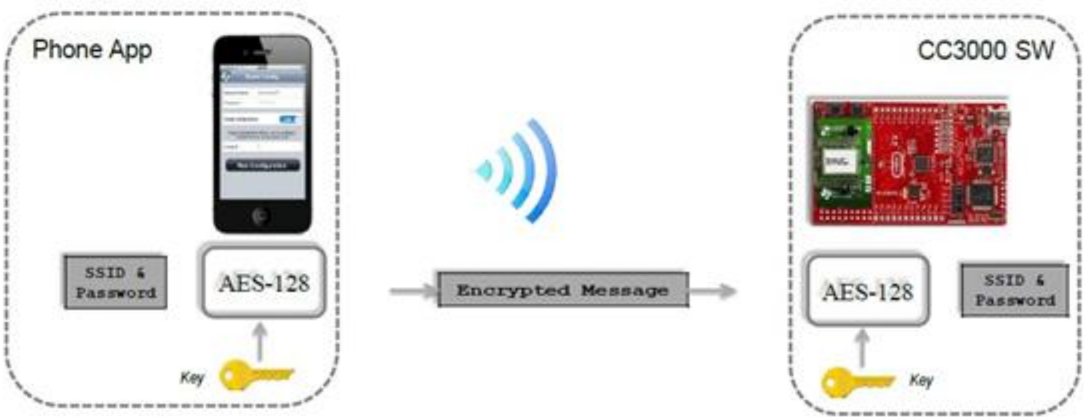


Figure 3-9. TI CC3000 Smart Config communication model [36].

The steps of Smart Config is as follows:

- The Wi-Fi module enters into Smart Config state when the user presses SW2 when the Wi-Fi adapter is powering up. The Wi-FI module starts probing UDP packets which contain information regarding the SSID and the key of the AP that the Wi-Fi module connects to.

- Once the Wi-Fi module receives all the association information, it generates an information packet to be saved in its EEPROM.
- The information exchanged between SmartConfig App and the Wi-Fi module is encrypted by using Advance Encryption Standard (AES) encryption method.
- Once the information is exchanged, profile information is saved in the EEPROM and the same information is used in every power cycle.

Figure 3-10. Snapshot of Smart Config app [36].

The user interface of the sample Smart Config app is shown in Figure 3-10. The app takes following parameters:

Table V. Smart Config parameter for Wi-Fi data logger

SSID:	AP's SSID is automatically detected or can be configured by the user.
Password:	AP's password in the case where WEP, WPA, WPA2 security is used.
Gateway IP Address:	AP's IP is automatically detected.
Key:	"TTT" for Wi-Fi data logger programmed in firmware.
Device Name:	"USASK-CAP" programmed in firmware.

The Wi-Fi data logger does not need to be configured on every power cycle. The Wi-Fi data logger should be configured once during the first-time start or if the network settings are changed. To activate the configuration mode, the user needs to press a button (labeled SW2 in Figure 3-11) when the Wi-Fi adapter is powering up.

3.5 Results

3.5.1 Data logger prototype

The data logger was prototyped into two iterations. In the first iteration, the Launchpad development kit from Texas Instruments was used for prototyping as shown in figure 3-11. The existing development kits were used to demonstrate proof of concept and software validation. The LM4F120 Launchpad [67] from Texas Instruments was used as processing unit. It has onboard debug interface for software debugging. The Launchpad was connected with the computer for flashing microcontroller, debugging and capturing status logs in serial terminal. CC3000 Launchpad from Texas instruments [68] was stacked on the top of Launchpad to add Wi-Fi functionality. Nordic nRF24L01 RF transceiver and battery/ battery charging unit was connected using jumper cables. Once the software was validated, a custom PCB was designed using Altium Designer version 15 PCB design tool. The PCB was designed using 2 layers design with top and bottom side components. The PCB design includes microcontroller, battery charging unit, external random access memory, USB connector and headers for external sensors. The 3D rendered of the design is shown in figure 3-12. The RF module was stacked at the bottom side of the PCB and the Wi-Fi module CC3000 was used in the PCB stacked at the top side of the PCB as shown in the Figure 3-13. The Wi-Fi and RF modules are chosen to be stacked with PCB to reduce the complexity of designing PCB using RF antennas. The Wi-Fi modules used in the design was

Federal Communications Commission (FCC) / Industry Canada (IC) and European Conformity (CE) certified. Data logger firmware was developed in Keil uVision version 4.74.0.22 with ARMCC compiler version 5.03.0.76. The HAL and CC3000 API was downloaded from Texas Instruments product download sites.

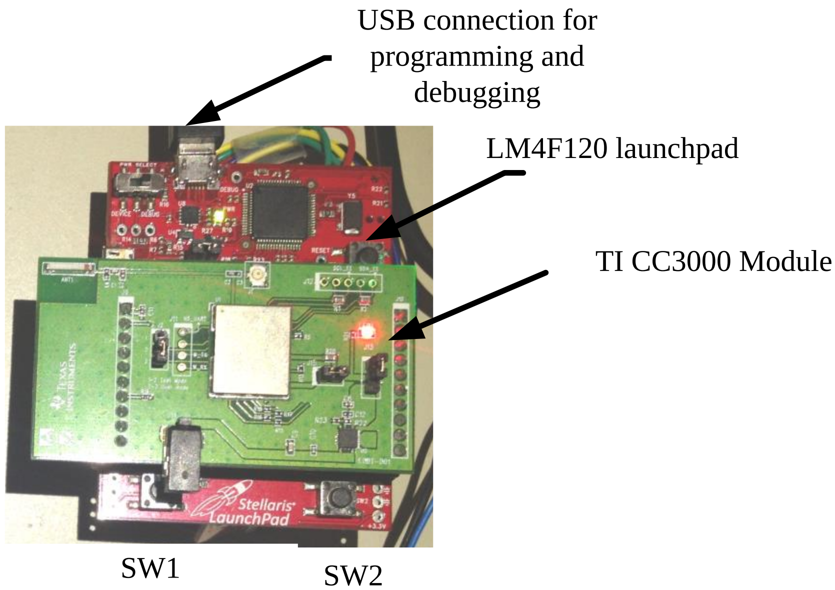
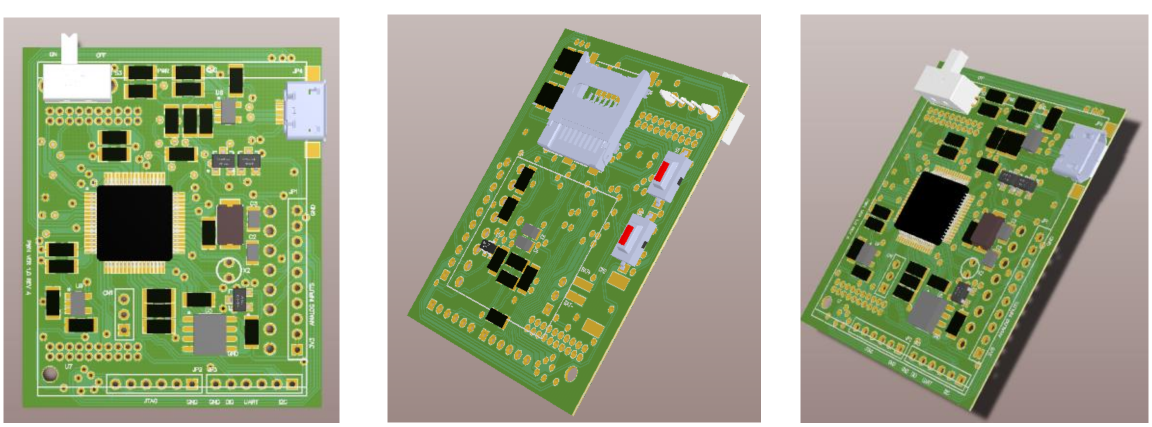
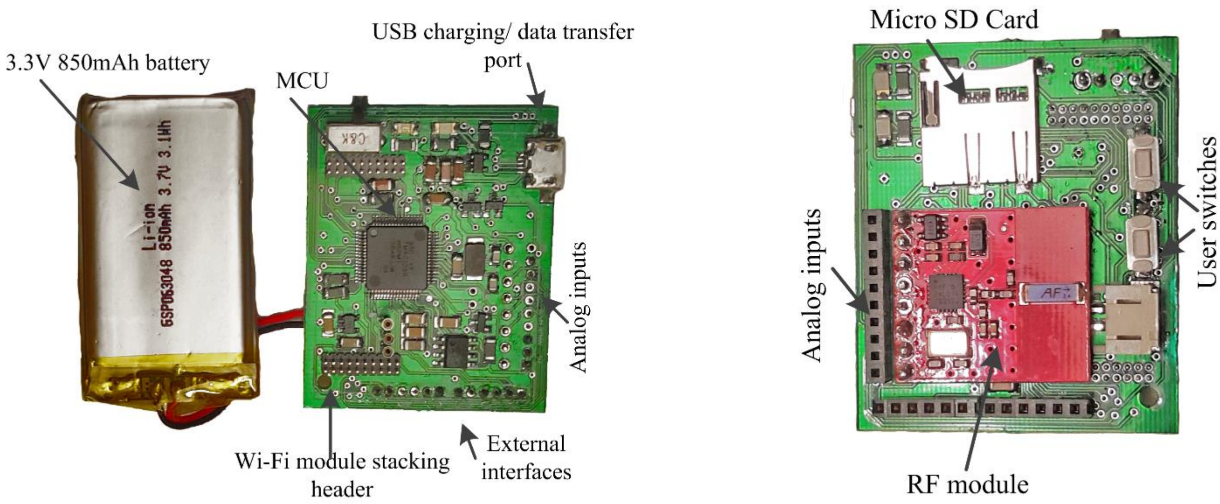


Figure 3-11. First iteration of the Wi-Fi Data logger.



(a) (b) (c)

Figure 3-12. 3D rendered design of Wi-Fi data logger in (a) front (b) back and (c) isometric view.



(a) (b)

Figure 3-13. Wi-Fi data logger PCB after assembly:(a) top view with battery and (b) bottom view with RF transceiver.

The PCB was designed in two layers with IPC medium density standard guidelines as specified for medical devices. The hardware design includes 1.27 mm pitch header for future expandability. One I2C, digital and analog interfaces are brought up in the male header. This header can be used to connect external module or peripheral device to expand the features of the data logger. This enables the proposed Wi-Fi based data logger modular and expandable in future. The mechanical and electrical parameters of the Wi-Fi data logger are shown in the table VI.

Table VI. Electrical and mechanical parameters of Wi-Fi data logger prototype

S.No.	**Parameters**	**Value**
1.	Dimension	46 mm×25mm ×40mm
2.	Weight	120 g (with battery and without enclosure)
3.	External Interfaces	2x Analog, I2C, UART and RF

3.5.2 Data logger power consumption

A detailed power consumption analysis was done on the Wi-Fi adapter. A hall effect based current sensor ACS712 [69] was used to measure current consumption in the peripherials of the data logger. The accuracy of current sensor is 1.5%. A current sensor module was purchased from sparkfun [69] and it was connected to 5V direct current power supply. The sense terminal of current sensor was connected to the voltage rails of RF transceiver, Wi-Fi module, LM47120 microcontroller and main board. The current was measured at different levels of activity of the Wi-Fi adapter, including powering up, transmitting, receiving and idle. Wi-Fi data logger is set to normal operating mode to acquire images from wireless capsule and send to mobile phone. The average current consumption in normal operation is noted to measure average power consumption of data logger components. A special modification in the firmware was done to measure power consumption of Wi-Fi data logger in different operating modes. A firmware was loaded in data logger which transmits stream of bytes to mobile phone via TCP/IP connection. The average power consumption in Wi-Fi module was measured in transmitting state. Similarly, a custom firmware was loaded in the data logger which receives stream of data bytes from mobile phone to the data logger. The power consumption was measured to find the average power consumption of Wi-Fi module when receiving data. Similar custom firmware was loaded in the data logger to measure power consumption in nRF24L01 RF module. The output of current sensor is voltage which is linear representation of current flowing through sensor. A voltmeter was connected to the output terminal of current sensor and average current consumption for 5 minutes were noted down. The power consumption of each device is shown in Figure 3-14.

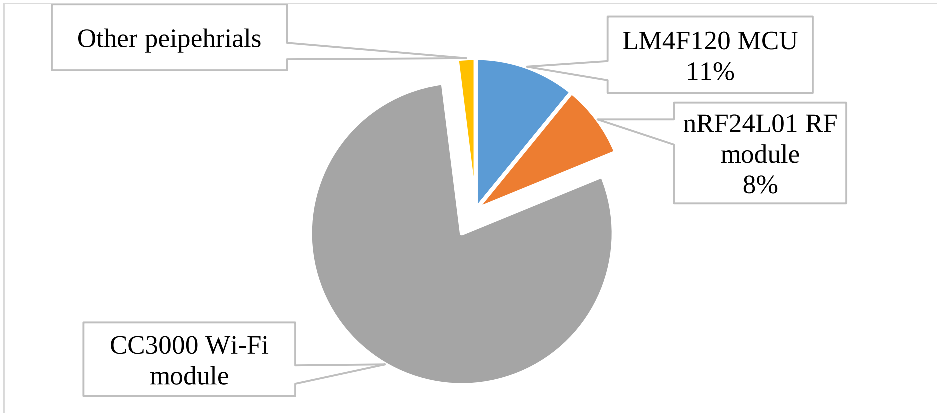
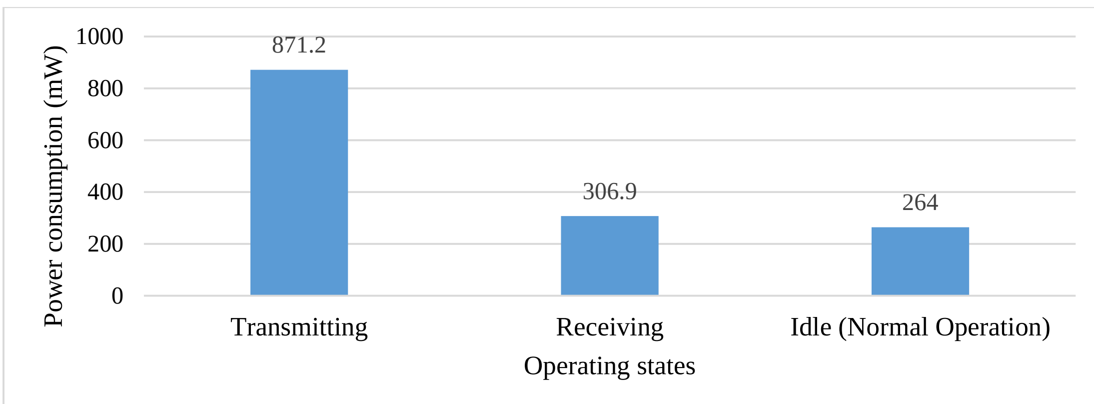
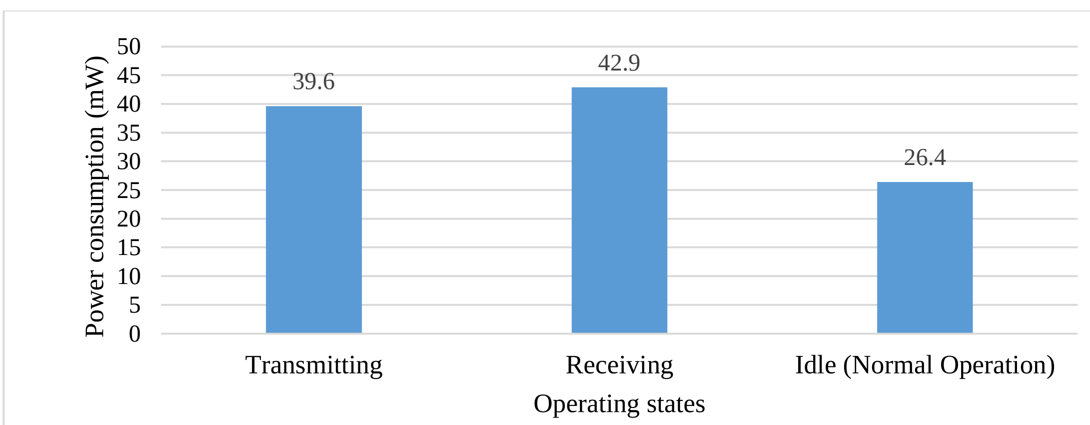


Figure 3-14. Average power consumption major components in Wi-Fi data logger.



(a)



(b)

Figure 3-15. Power consumption of (a) CC3000 Wi-Fi module and (b) nRF24L01 RF module at different states.

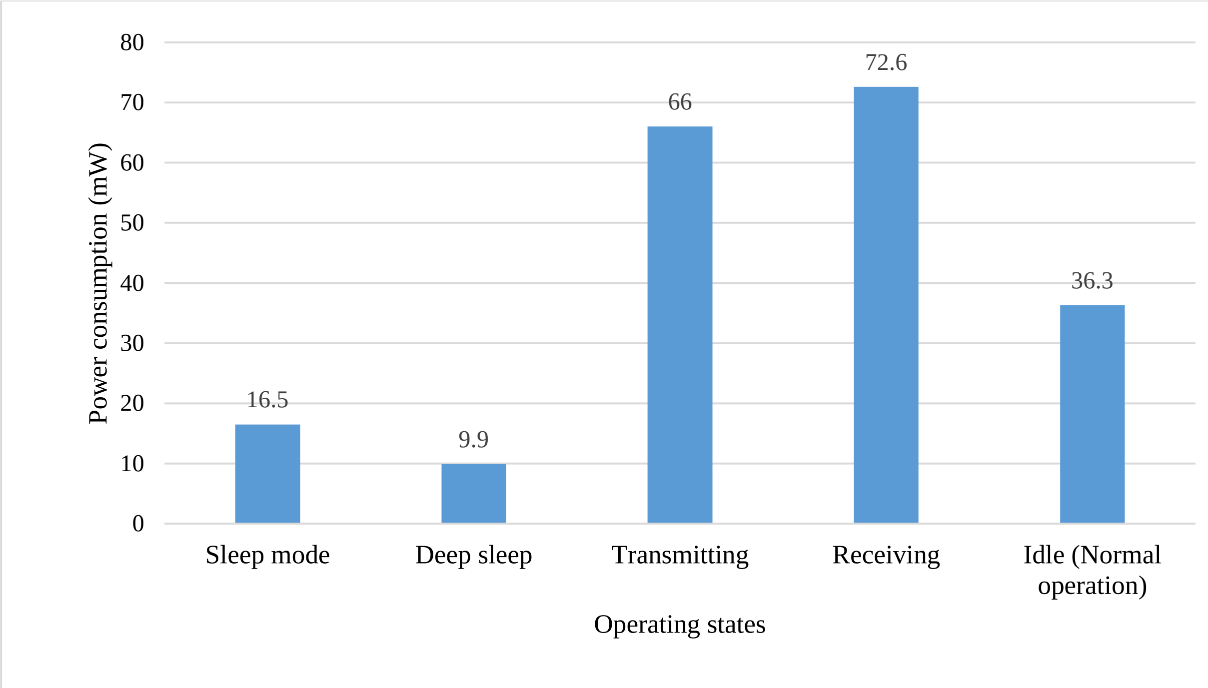


Figure 3-16. Power consumption of LM4F120 microcontroller at different operating state.

From power consumption analyses (figure 3-14), it was found that the Wi-Fi module consumes 79%, nRF24L01 RF transceiver consumes 8%, and LM4F120 consumes 11% of total power in the data logger. This suggests that power consumption in Wi-Fi is considerably high compared to other peripherals in the design. The power consumption of Wi-Fi, RF transceiver and microcontroller in different states and average power consumption at normal working environment is illustrated in Figures 3-15 and 3-16. Figure 3-16 suggests that we can further reduce the power consumption of microcontroller below 36.3mW using sleep features in firmware. The firmware in data logger continuously monitors activity in Wi-Fi and RF interfaces. The microcontroller starts inactivity timer when both Wi-Fi and RF interfaces are inactive. After 5 minutes of inactivity, the inactivity timer generates signal to enable sleep mode. The firmware switches microcontroller to sleep mode by configuring sleep mode in the configuration register described in the datasheet. The microcontroller wakes up from sleep when it receives interrupt signal from Wi-Fi or RF module.

Similarly, we can implement power saving features in Wi-Fi and RF transceiver modules to reduce overall power consumption. The nRF24L01 RF transceiver can set into power down, Standby-I and Standby-II power modes. In power down mode, the RF transceiver disabled with minimum current consumption. In power down mode, communication between RF transceiver and microcontroller is possible but RF communication is disabled. In Standby-I mode, only crystal oscillator is enabled for faster wake up time. In Standby-II mode, phase locked loops and crystal oscillators are up and enabled. The power saving features are set into RF transceiver by configuring PWR_UP, PRIM_RX registers as described in the datasheet [29]. Similar power saving features are available in Wi-Fi module [33]. These power saving features in RF and Wi-Fi modules are not implemented in current firmware of data logger. From the plot, it is shown that the average power consumption is lower than transmitting and receiving states. This is because the data is transmitted/received in burst mode, not in a continuous manner. The image data from wireless capsule is transmitted at the rate of 2 frame per seconds. After transmitting an image, the wireless capsule stops transmission and start acquisition of new image. During this time, there is no activity in RF transcievers. The RF transcievers stays in idle mode. It emulates the data communication between data logger, mobile and wireless capsule as brusts of data.

The designed data logger has a 3.7V/850mAh lithium-ion battery, which gives a battery runtime of 8.4 hours with continuous usage of the RF and Wi-Fi interfaces. When Wi-Fi is disabled and offline logging is enabled, the battery runtime increases to 40.4 hours. The battery runtime of 8 hours is sufficient for one session of wireless capsule endoscopy diagnosis. The battery run time depends on operating temperature, battery charge cycle and battery usage history. The provided calculations do not include these factors for simplicity. The battery runtime calculation is summarized in Table VII.

Table VII. Battery runtime calculation for different operating modes.

S.No.	Operating mode	Total power consumption (average)	Average battery runtime (using 3.6V/ 850mAh battery)
1.	Wi-Fi enabled	333.3 mW	8.4 hours
2.	Wi-Fi disabled	69.3 mW	40.4 hours

3.5.3 Wi-Fi interference

The issue of using a Wi-Fi based device is susceptibility to interference from other Wi-Fi enabled devices. Wi-Fi enabled devices are increasingly becoming popular, and the Wi-Fi operating frequency channels are crowded day by day. A detailed interference profile was conducted on the developed prototype to study the effect of surrounding Wi-Fi enabled devices using the Wi-Fi analyzer app in Android smartphone. The plot between numbers of retries (try to send data packet average of 1 second) versus. the number of Wi-Fi networks available in the test area is shown in Figure 3.17. The Wi-Fi data logger was loaded with custom firmware to count the number of retries to send a data packet to the host computer. The test area was varied according to the availability of a number of Wi-Fi networks on the 2.4 GHz band. From Figure 3-18, it is shown that number of retries keep increasing when there were more than 8 Wi-Fi networks in surrounding. The Wi-Fi network is strong towards noise from other devices at the same frequency band. This is due to the fact that Wi-Fi continuously hops to noise-free channels for data transmission.

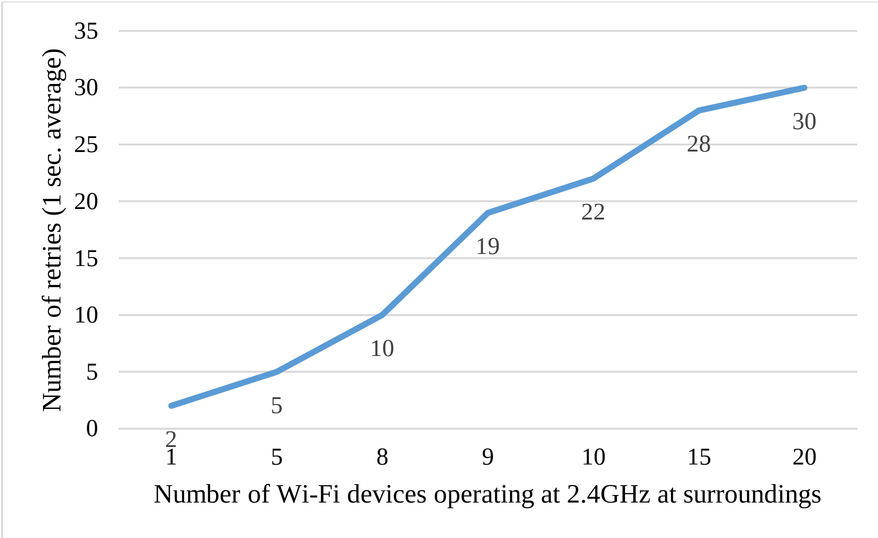


Figure 3-17. Plot of a number of retries vs. a number of surrounding Wi-Fi devices.

CHAPTER 4

ANDROID APPLICATION

4.1 Introduction

WCE data processing application is an essential component of the wireless capsule endoscopy system. The data logger saves captured images from the capsule and those images are decoded, reconstructed and displayed for medical diagnostics in the workstation. In our proposed architecture, a Wi-Fi based data logger can send captured image data directly to an Android-based smart device, which then decodes, processes and presents the image data to the viewer. In this chapter, the design of Android app for Android smart devices for WCE is outlined.

4.2 Design requirements

Android application is expected to have following capabilities:

- The application should be able to receive data from a TCP/IP interface.
- The application should contain TCP/IP connect, disconnect features and the application should act as client while the data logger always acts as TCP/IP server.
- The application should contain decompression or decoding algorithms to reconstruct images from compressed data for different WCE images.
- The application should be able to send a proper command to the capsule according to the features selected by the user via the GUI.
- The application should be able to save the reconstructed images in BMP format.
- The application should display the images captured from a capsule real-time.
- The application should have supporting applications only for decoding and displaying the stored imaged from the storage device.

4.3 Android application

Two different Android apps were developed to fulfill the design requirements. An Android app collects data from the capsule through Wi-Fi data logger and another application decode and displays the images from the storage device. The two apps are called WCE logger and WCE viewer. Android software development kit ADK with API level 14 was used to develop Android apps. At the time of development. An Eclipse integrated development kit (IDE) with java was used as software development platform. The Android app was targeted to run in Android 4.0 or later versions.

4.4 WCE Logger and viewer app

The WCE logger/viewer app is responsible for setting up TCP/IP connection with Wi-Fi data logger, executing a proper command to send data to the capsule and receive data from the Wi-Fi data logger. The Android app was designed in three different layers, namely application layer (foreground services), middleware (background services) and device drivers. The basic architecture of the WCE app is shown in Figure 4-1.

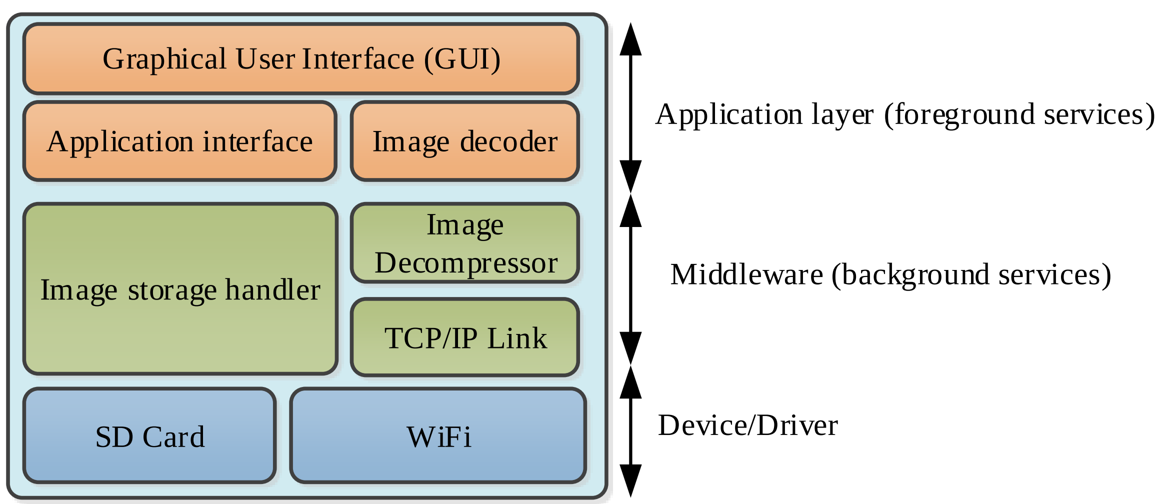


Figure 4-1. Architecture of the WCE logger application.

The low-level device drivers and the protocols were already implemented in the Android operating system so that there was a minor addition to the device/ driver layer. The device driver of Wi-Fi and SD card are managed by operating system low-level board support packages. The proposed application operates on the application layer and middleware. The middleware is also called background services as this level is hidden from users. There are three basic components in background services, including:

a. Image storage handler
b. TCP/IP Link
c. Image decompressor

4.4.1 Image storage handler

Image storage handler is responsible for decoding image into the correct format to save into the storage device. For document portability, the windows bitmap (BMP) file format was used to save image data into the storage device.

4.4.2 TCP/IP Link

TCP/IP Link service is responsible for connecting the host server (Wi-Fi data logger) at given IP address and port number. The TCP/IP was chosen as communication layer for error free communication between server and client. The Wi-Fi data logger takes the role of server, and smart device, smartphones, and the computer takes the role of the client. Single Wi-Fi data logger can handle three clients simultaneously. As TCP/IP is a connection oriented network, communication should be established before the data communication.

4.4.3 Image decompressor service

Image decompressor service is responsible for decompressing data arriving from the data logger. This service is optional and can be modified according to the application. In wireless capsule endoscopy where images are transmitted from wireless capsule to external data logger, bandwidth is a bottleneck for transmission of high-resolution images at high frame rate. The RF transceiver used in wireless capsule limits the speed of data transfer hence affecting the size of an image and maximum frame rate possible to transfer from wireless capsule. To address this problem, several image compression algorithms are developed for capsule endoscopy systems [7] [37]. An image data is compressed in wireless capsule and later decompressed in data logger. In our proposed architecture, image decompression is performed in the mobile device. The proposed Wi-Fi data logger was designed to operate with wireless endoscopic capsule developed in our lab here at the University of Saskatchewan [7]. The proposed wireless capsule was designed to compress image data in wireless capsule and decompress in the data logger. The compression algorithm is discussed in [7] and [37] and beyond the scope of this thesis.

Foreground services include application interface, image decoder and graphical user interface. The application interface includes a collection of subroutines to interface background services such as image decompression, initiate communication, save, load data, etc. The graphical user interface gives an interactive user interface for taking user inputs and presenting outputs to the user. The user can provide necessary inputs like IP address, capsule command format, and initiate data communication. The GUI also provides information on the number of images acquired, a total number of files saved and the current communication status. The image decoder service is responsible for decoding bitmap data to present images in smart device screen.

4.5 Multithreading processes

The application is multithreaded so that communication between the application and the background services are synchronized with each other. Each thread communicates with other threads using flags. This increases the effectiveness of processor usage. The image decoding can be performed while the application is receiving data from the data logger. The lower level functions like image storage handler, image decompressor and TCP/IP link and GUI is handled in different threads. An overview of the multithreading is shown in Figure 4-2.

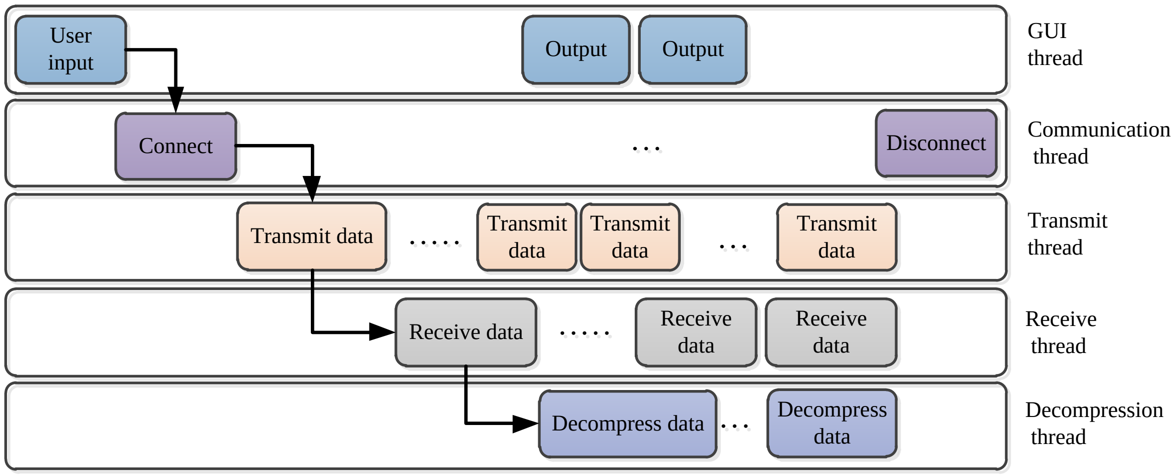
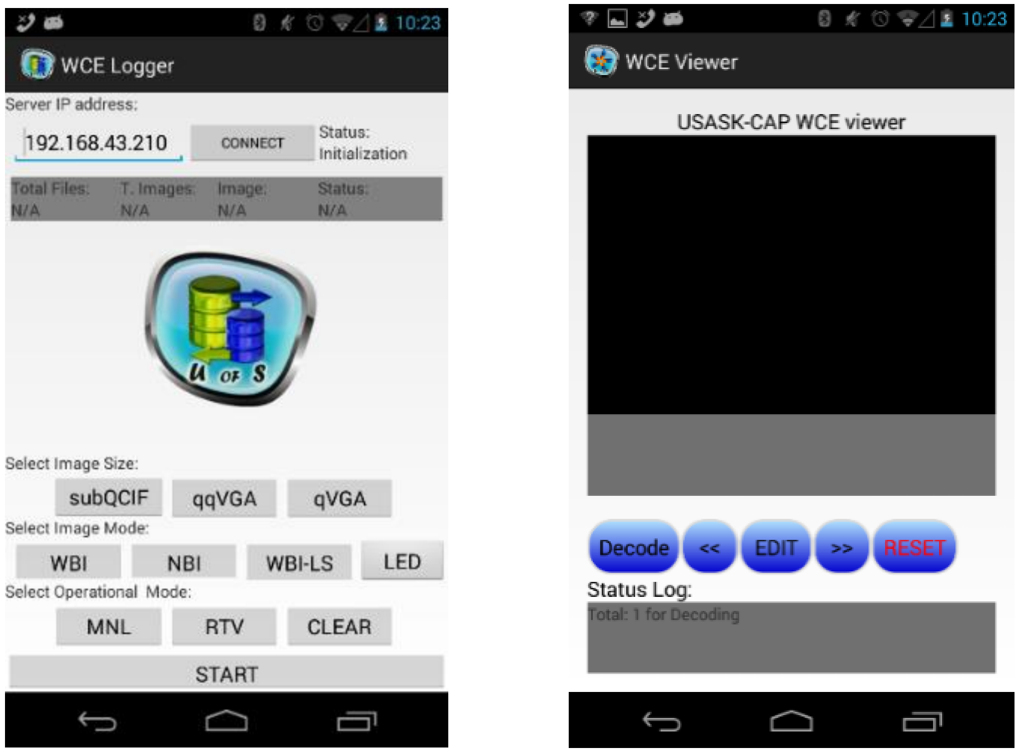


Figure 4-2. Multiple threads in the WCE Android app

4.5.1 Graphical user interface thread (GUI) thread

GUI thread handles all user interface related tasks like buttons, user inputs, outputs, image display and options. The GUI thread is responsible for capturing inputs from the user and sending it to other threads. The GUI updated the outputs like a number of images captured, the number of files saved, the number of images updated and connection status on real-time. The GUI of the Android app is shown below:



(a) (b)

Figure 4-3. GUI of (a) WCE logger app and (b) WCE viewer app.

The user input options are shown in Figure 4-4. The user inputs are customized to fit for wireless capsule developed in our lab here at the University of Saskatchewan [38]. The top level menu includes IP address input and connect/disconnect button. This enables the user to input the IP address of the Wi-Fi data logger for initiating communication. Data communication is possible after the establishment of a communication link between the Android device and Wi-Fi data logger. The other options are related to the capability of wireless endoscopic capsule device. The wireless capsule proposed in [38] is configurable to capture images of different sizes subQCIF, qqVGA and qVGA. There are four LED's in the wireless capsule, among them two are white LED for wide band imaging and one green and one blue LED for narrow band imaging applications. The LED can be continuously turned ON during image acquisition, or LED can be turned OFF when the wireless capsule is not capturing images to save power. The application can operate in two different modes: Manual (MNL) and Auto (AUTO). In manual mode, the only single image frame is captured per command but in Auto (AUTO) mode, subsequent image capture is initiated once the previous image acquisition is finished. The application can also be used in Real-time View (RTV) mode for real-time image viewing. The captured image is decoded and presented to the user in real-time.

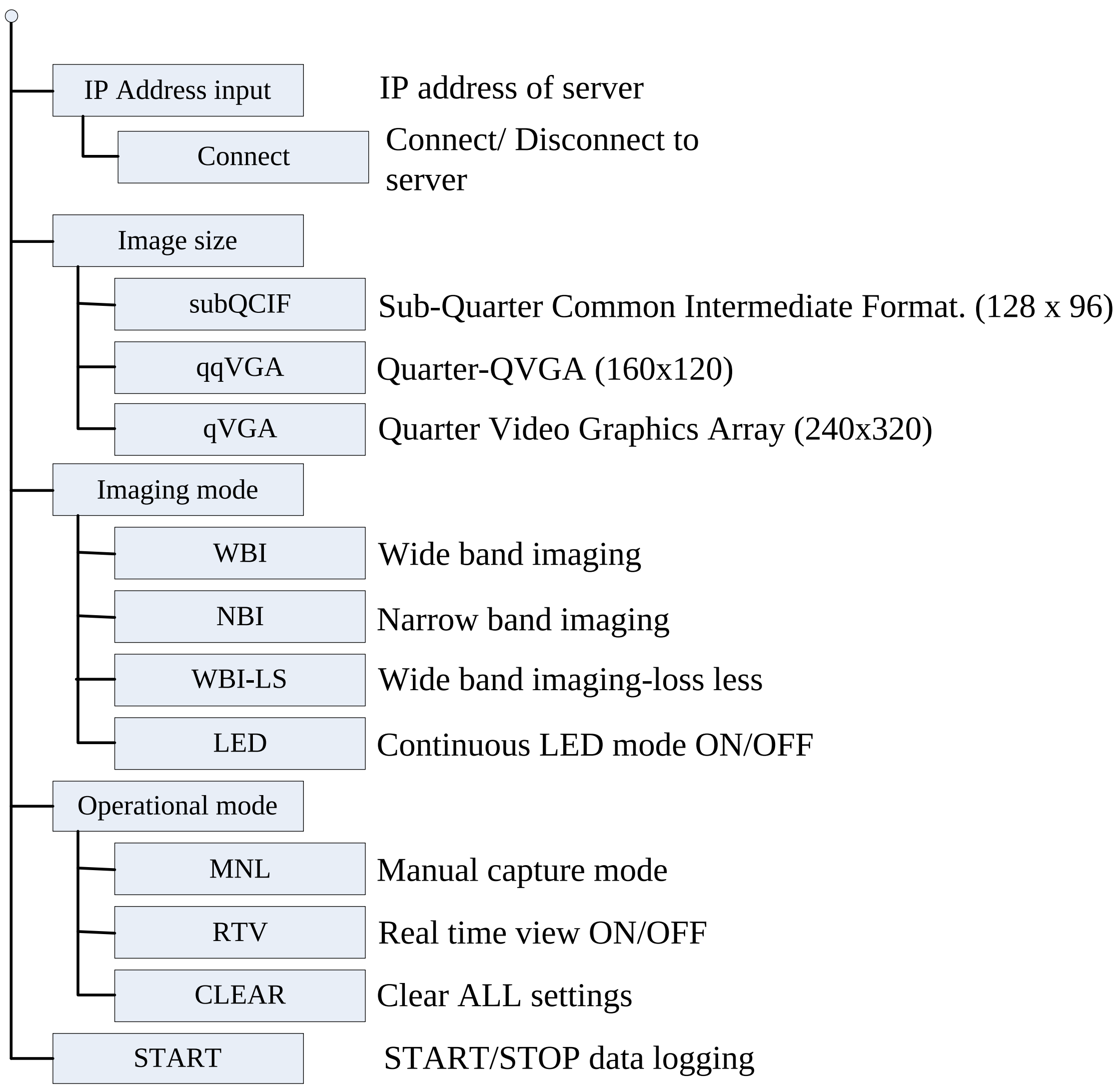


Figure 4-4. Menu tree of the Android app GUI.

4.5.2 Communication thread

The communication thread is responsible for establishing a TCP/IP link with the Wi-Fi data logger and maintaining the communication during data acquisition. This thread becomes active when the user initiates the ‘CONNECT’ command. The thread terminates when the user terminates communication using the ‘DISCONNECT’ button.

4.5.3 Transmit/Receive thread

The transmit/Receive thread is responsible for transmitting commands and receiving data from the Wi-Fi data logger. It maintains data integrity and synchronizes the FIFO memory so that the received data is not overlapped when capturing image data.

4.5.4 Decompression thread

Once data is saved into memory and the complete image frame is received, and the real-time view (RTV) option is enabled, the decompression thread initiates the image decompress process. The image decompression algorithm depends on the compression method used in the wireless capsule. In this version of the app, the image decompression algorithm proposed in [37] was implemented. The detail discussion of an image compression algorithm is beyond the scope of this thesis. The image decompression algorithm can be easily changed by modifying the decompression process only.

CHAPTER 5

EXPERIMENTAL SETUP

5.1 Introduction

The proposed Wi-Fi based data logger was tested with a wireless endoscopic capsule [7] prototyped in our laboratory. The data logger can be operated in different configurations according to the Wi-Fi network availability. The Wi-Fi based data logger can operate in two different environments.

5.2 Wi-Fi modes

Wi-Fi devices can be used into two different modes: i) Infrastructure mode; and ii) Ad-Hoc mode. Infrastructure mode is widely used in public and private places to connect internet and intranet networks. Moreover, Ad-Hoc mode is used to connect Wi-Fi devices without using additional Wi-Fi managed devices like routers and gateways. These two operating environments are described in the following sections.

5.2.1 Infrastructure environment

In infrastructure environment, all Wi-Fi devices (clients) are connected to access points (AP) which manage the connections. In this mode, we need access point (AP) hardware to moderate communication between the data logger and the smart device. Once powered up, the data logger obtained an IP address from the access point. The smart device which is intended to collect data from data logger needs to be connected to the same Wi-Fi network. The data logger acts as TCP/IP server and corresponding smart device acts as TCP/IP client. For easy configuration, the data logger can have static IP address so that we do not need to check the IP address assigned to the data logger. The basic setup in infrastructure mode is shown in Figure 5-1.

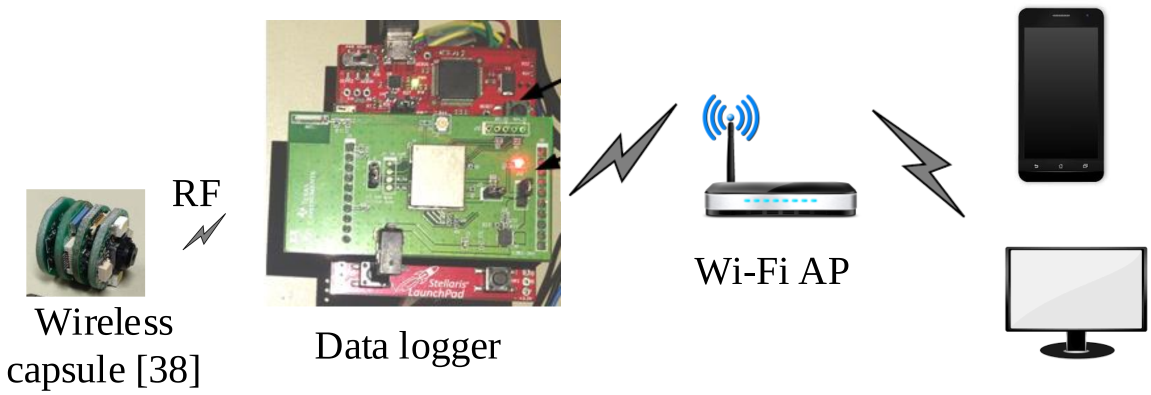


Figure 5-1. Data logger used in Wi-Fi Infrastructure environment.

5.2.2 Ad-hoc environment

In Ad-hoc environment, the smart device acts as an access point, and the data logger connects to the smart device without using the additional Wi-Fi device. This environment is useful when there is no Wi-Fi infrastructure present and need to create Wi-Fi network. This can be achieved by using Ad-hoc mode in the smart device or Wi-Fi tethering. Figure 5-2 shows the data logger used in Ad-hoc environment. The proposed data logger can be used in an Ad-hoc environment where there is no existing Wi-Fi network available.

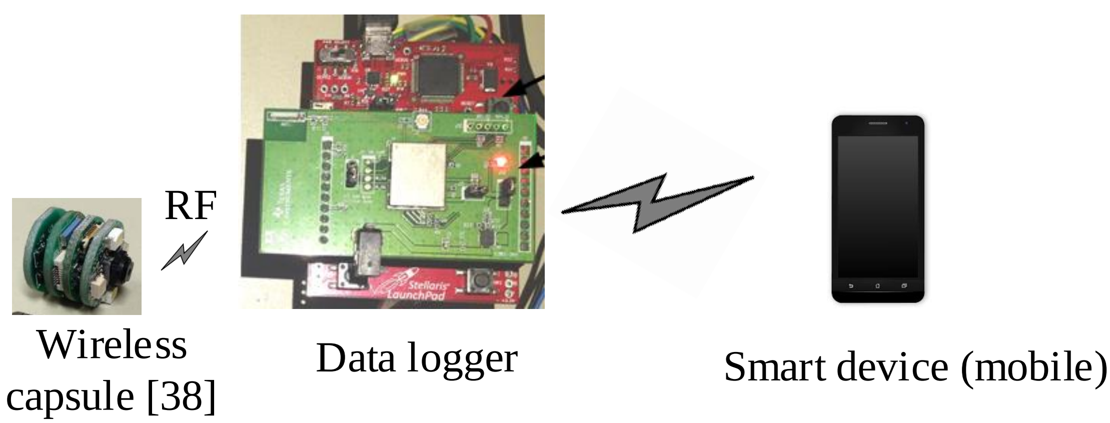


Figure 5-2. Data logger used in the Wi-Fi Ad-hoc environment.

5.3 Wireless capsule communication

The proposed data logger communicated with the wireless capsule using a 2.4GHz ISM RF transceiver. The transceiver described in Chapter 3 is compatible with the RF transceiver used in the wireless capsule. The communication protocol between the wireless capsule and data logger was customized to fit our purpose the detail communication protocol is explained in later sections. The process of information exchange is illustrated in Figure 5-3. Once powered up, the RF transceiver set into idle mode. The RF transceiver in wireless capsule set in receive mode. Once the command was sent from the smart device to the data logger via TCP/IP, the RF transceiver changed the mode to the transmitter and sent a command to the wireless capsule. The format of the command is one-byte packet structure as shown in Figure 5-4. In the response, the wireless capsule processed command and captured image data according to the request, then compressed image data and transmitted image data to the corresponding smart device. The response data from the wireless capsule is of variable length, and the end of data is indicated by four consecutive zero bytes as shown in the Figure 5-5.

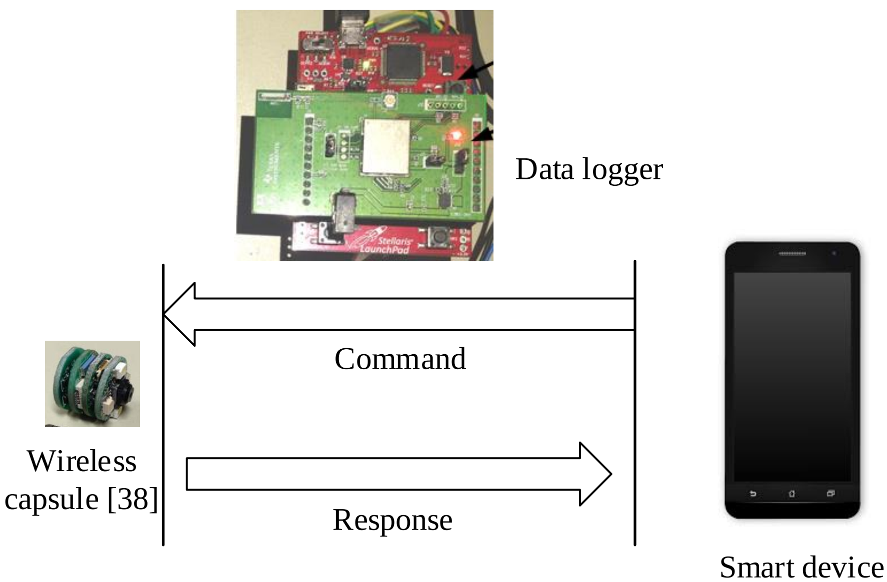


Figure 5-3. Communication between smart device and wireless capsule.

	Command packet (1 Byte)							
Bit	7	6	5	4	3	2	1	0
	S	C	L1	L0	M1	M0	S1	S0

Figure 5-4. Command packet format. The bit combinations are explained in the table VIII.

The command packet is composed of 8 bits. This makes the communication between smart device/ data logger to wireless capsule consistent. The 7th bit of the command is reserved to indicate the start of the command byte. The LSB bit 0 and bit 1 indicated the requested image size. The details of S0, S1 bit combinations is shown in Table VIII. Similarly, bit 2 and bit 3 indicates the requested mode of imaging. The wireless capsule supports three different modes; wide band imaging (WBI- lossy), narrow band imaging (NBI), and wideband imaging (WBI-lossless) as explained in Chapter 2. The bit 4 and bit 5 indicates which LED to turn ON during image acquisition. The 6th bit sets the LEDs operating mode. LED can be continuously turned ON or can be turned ON only when acquiring images. The '1' in this bit enables LED continuously and '0' in this bit enables LED only when wireless capsule is capturing an image.

Table VIII. Command packet data bits.

S1	S0	Size
0	0	subQCIF (128x96)
0	1	QQVGA (160x120)
1	0	QVGA (320x240)
1	1	VGA (640x480)

M1	M0	Mode
0	0	WBI-lossy
0	1	NBI
1	0	WBI-lossless
1	1	Reserved

L1	L0	LED
0	0	White
0	1	Green
1	0	Blue
1	1	All LED OFF

The command packet structure is configurable according to the device connected to the data logger. As communication between the wireless capsule and data logger is transparent, the data bytes sent from wireless capsule arrives in mobile devices without any addition of data bytes. There is no need for firmware changes to interface other sensors in the data logger.

<table>
<tr><td></td><td colspan="15">Response data packet (Variable length)</td></tr>
<tr><td></td><td colspan="8">Start Byte (1 Byte)</td><td>….</td><td>….</td><td>….</td><td colspan="4">End bytes (4 Bytes)</td></tr>
<tr><td>Bit</td><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>0</td><td colspan="3" rowspan="2">Payload</td><td colspan="4"></td></tr>
<tr><td></td><td>0</td><td>C</td><td>L1</td><td>L0</td><td>M1</td><td>M0</td><td>S1</td><td>S0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
</table>

Figure 5-5. Response data packet structure from the wireless capsule.

The response data structure from wireless capsule is shown in Figure 5-5. The response from wireless capsule always starts from start byte with 0 on starting bit. Rest of data bits in the start byte is similar to the command byte. It makes the data processing unit to identify the size and mode of captured image. The length of the payload can be variable length, but the response data packet always ends with four consecutive zero bytes. This end of packet pattern was chosen due to the fact that the compression algorithm used in the wireless capsule never generates four consecutive zero bytes.

5.4 Wide band imaging (WBI) and narrow band imaging (NBI)

The wireless capsule can capture images in two different lighting modes namely wide band imaging (WBI) and narrow band imaging (NBI). In WBI, white LED with wide spectrum (400nm to 700nm) was used for capturing images. The object's absorption and reflection characteristics are different in different wavelengths. In wireless capsule prototype, green and blue LEDs were used during NBI image acquisition. First, the single image frame was acquired using the blue light of 420nm, and another image frame was captured using green light of 500nm. The image frames were then transmitted to the data logger, and color reproduction algorithms were used to combine blue and green frame to reproduce the full-color image. The use of NBI mode helped to highlight special tissues structure in the endoscopy application [40]. The process of reproducing a color image using NBI frames are shown in Figure 5-6. The switching time between green LED and blue LED was 29.78ms, as shown in Figure 5-7. This delay time was determined by the internal programming of wireless capsule. The movement of the wireless capsule was pulsating (i,e., discontinuous) hence we captured image frame from a relatively the same position using two different lightings at 29.78ms.

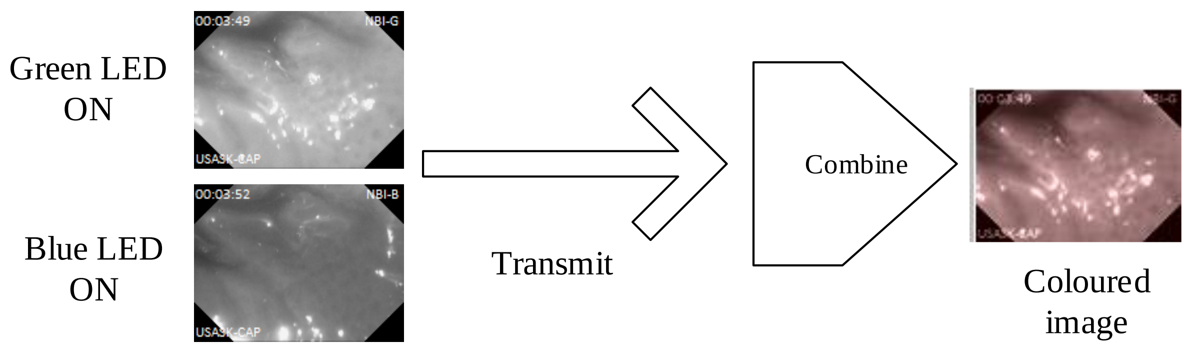
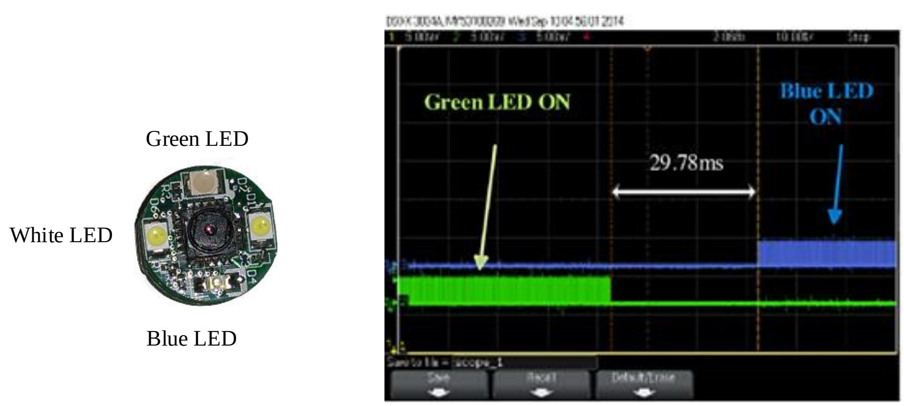


Figure 5-6. Image captured in NBI mode.



(a) (b)

Figure 5-7. (a) Green and blue LEDs in capsule [38] (b) switching time in NBI mode (green waveform shows the green LED turn ON time and blue waveform shows the blue LED turn ON time)

CHAPTER 6

EXPERIMENTAL RESULTS

6.1 Introduction

To validate the concept and the Wi-Fi based data logger design, the Wi-Fi data logger along with the developed Android app was tested in a different scenario. The Wi-Fi data logger was designed to work with wireless capsule prototype developed in the lab of University of Saskatchewan [38]. Existing wireless capsule endoscopy system consists of wireless capsule with a TCM8130MD CMOS image sensor from Toshiba, MACHXO2 CPLD from Lattice, power regulators and nRF24L01 RF transciever. The data logger with LCD, RF transciever, micro controller and USB connection was developed in the lab [39] Existing data logger did not have Wi-Fi interface so that it was not possible to use with smart devices. The developed Wi-Fi data logger was used in the exeriments to collect images from wireless capsule into smart phone, tablet and/or computer. After getting the ethical permission from Animal Research Ethics Board (AREB) [60] for conducting tests involving animal. A portion of pig's small intestine was collected from the Praire Swine Center [41] and experiment with pig's intestine was conducted in the anatomy lab of Western College of Veterinary Medicine without RF shielding [59]. Next experiment with live pig was conducted in Prairie Swine Center [41]. The objective of these experiments was to validate the operation of Wi-Fi data logger and the smart device based application. The experiments are briefly described below.

6.2 Experiment with pig's intestine

In this experiment, the capsule prototype and Wi-Fi data logger with the Android app was used to validate the design and performance (such as image data loss, distance of communication, RF transmission issues etc.). Since fabricated PCB's were not available at the time of experiment.

the first prototype of Wi-Fi data logger was used in the experiment. Before the experiment, the operation of wireless capsule was validated using conventional data logger [39]. The setup of the experiment is shown in Figure 6-1. The LEDs brightness of wireless capsule was adjusted according to the ambient light of the room. The wireless capsule was inserted into the pig's intestine, and images were captured and decoded in real-time. There were two other Wi-Fi networks on the lab in the experiment area. The Nexus 4 smartphone was used as a Wi-Fi hotspot for creating a private Wi-Fi network. The Wi-Fi data logger was then configured to connect with the Nexus 4 smartphone using the secured Wi-Fi hotspot. Once the Wi-Fi data logger and Nexus 4 smartphone were connected using the WCE logger application, the commands to capture, images were sent to the wireless capsule. The 20 images of size subQCIF, qqVGA and qVGA were captured in WBI, NBI, auto, manual modes of two different positions of the intestine and saved into the internal memory of Nexus 4 smartphone. Once the experiment was finished, the raw files were downloaded to a decoding computer for image decompression. Images with real-time view enabled were already decoded and saved in BMP format in the internal memory of Nexus 4 so that no further image decompression was needed.

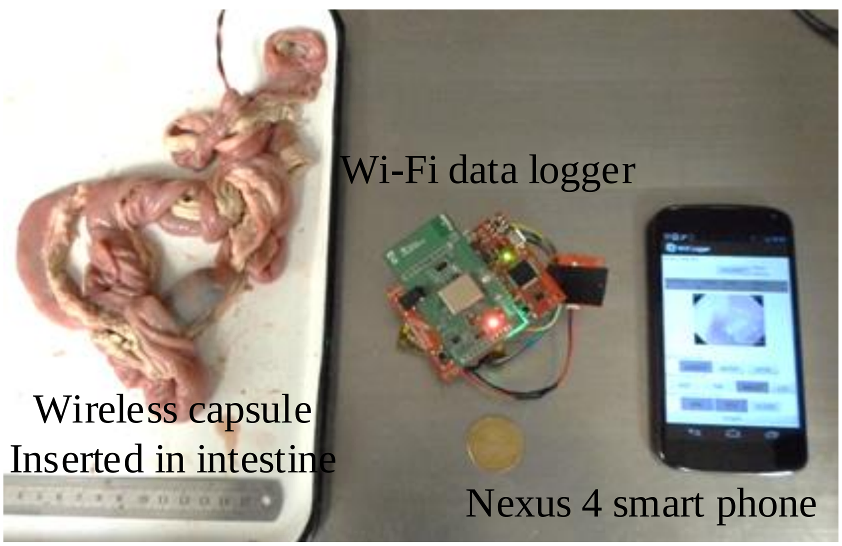


Figure 6-1. Capsule inserted in pig's intestine.

6.2.1 Results and Discussion

The Wi-Fi data logger successfully captured images transmitted from the capsule and sent it to Android based mobile phone (Nexus 4). The images were correctly decoded and saved without errors and distortions as shown in Figure 6-2. In this experiment, the capsule prototype was also covered by approximately 40mm thickness of extra intestine to simulate effect of skin and flesh over the intestine. The distance between the capsule and Wi-Fi data logger is varied from 0.3 meter to 2 meters and images were successfully transmitted from the distance of 2 meters. This distance is sufficient for the purpose of wireless capsule endoscopy. The data logger is designed to be worn by the patient, hence data logger will be in proximity of less than 0.3 meter from the body. The images of different size were captured and stored on the smart phone. In this experiment, images were captured without loss of image frames. The detailed features of the mucosa and small intestine were visible in all captured images. The developed Wi-Fi data logger and Android app worked properly during experiment. The images were captured at the rate of 2 frame per seconds. The frame rate decreased when the real-time view (RTV) was enabled as decoding images and displaying blocked the next image acquisition process. When RTV was disabled, the Wi-Fi data logger sustained at 2 frames per seconds image acquisition. The captured image data were saved in the binary file with file extension CE1 (Capsule Endoscopy1). Image size was set to qqVGA (160x120 pixels) and 96 images were captured continuously without real-time view to test the average compression ratio. There were total 1020 Kbytes of data received from the capsule. The Average size of compressed image was 10Kbytes. The size of an image after decompression was 57 Kbytes which gave the average image compression ratio of 82%. The compression ratio matches the compression ratio reported using wireless capsule and conventional data logger in [37].

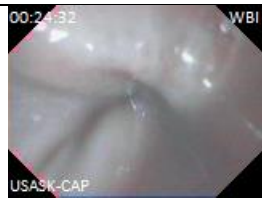
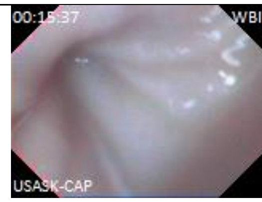
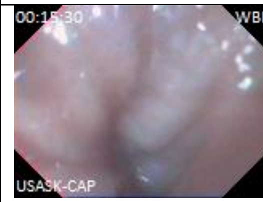
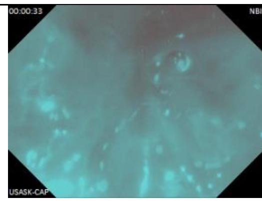
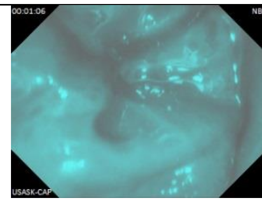
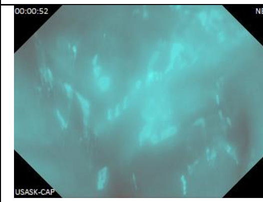
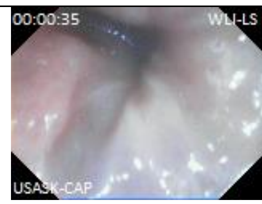
Size/Mode	subQCIF	qqVGA	qVGA
WBI			
NBI			
WBI-LS			

Figure 6-2. Captured imaged from pig's intestine.

6.3 Experiment with live pig

This experiment was conducted to verify the operation of Wi-Fi data logger in the real environment and observe the effect of the skin and muscle in data transmission. Here, anesthesia was applied to a live pig and the wireless capsule was inserted into its small intestine through surgery in its abdomen. The capsule was not easily inserted inside pig's intestine due to size of capsule. The diameter of capsule was 16mm which created challenge to insert capsule through small opening in abdomen. To solve this issue, opening of the intestine was taken out from surgery hole, then capsule was inserted and opening of the intestine was reinserted to the pig's body. The Wi-Fi data logger was placed in the distance of 5 cm from the pig's body. The images were captured into two different positions of the small intestine. Since capsule was not able to move naturally, the position of capsule was changed manually by removing and reinserting it in the pig's intestine into different position. During image transmission, the capsule was inside the pig's body. The Nexus 4 smart phone and Nexus 7 tablet was used to validate the performance of Wi-Fi data logger.

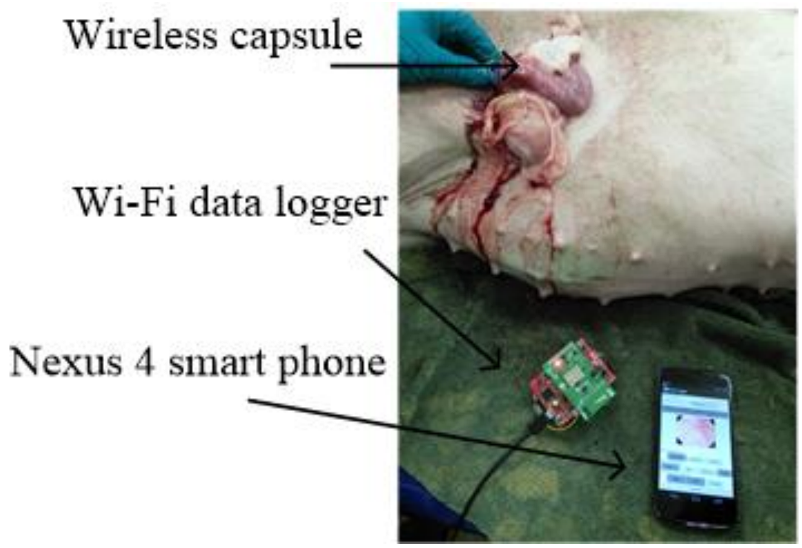


Figure 6-3. Capsule inserted in live pig's intestine.

6.3.1 Results and Discussion

The objective of this experiment was to validate the performance of Wi-Fi data logger when used in real world environment. Images were successfully captured from inside pig's body (intestine) without any loss of data. The captured images are shown in Figure 6-4. The mucosa and other features of pig's intestine was clearly visible in the captured imaged. Both WBI and NBI images were captured without any issues. Error in single bit in data transmission creates artifacts (black pixels) in the decompressed image. The captured images did not show no such artifacts. This suggests that there was no error in the data stream.

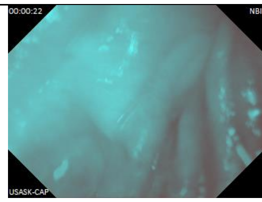
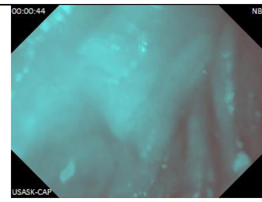
Size/Mode	subQCIF	qqVGA	qVGA
WBI			
NBI			

Figure 6-4. Captured imaged from live pig’s intestine.

6.4 Experiment with external sensors

The proposed hardware is programmable, general purpose and versatile. The same hardware and software architecture can be used for data collection from other medical sensors like heart rate and temperature sensors with the wireless capsule endoscopy system. We tested the data logger with two sensors: pulse sensor [50] and temperature sensor [51]. An Android application was developed to support these two sensors. The setup of the experiment is shown in Figure 6-5. The data logger was connected with the heart rate sensor using an analog interface and temperature sensor using an additional sensor node [52]. The sensor node had a medical sensor, a processor and a RF transceiver. The data logger collected data from both wired and wireless sensors and sent it to the smartphone.

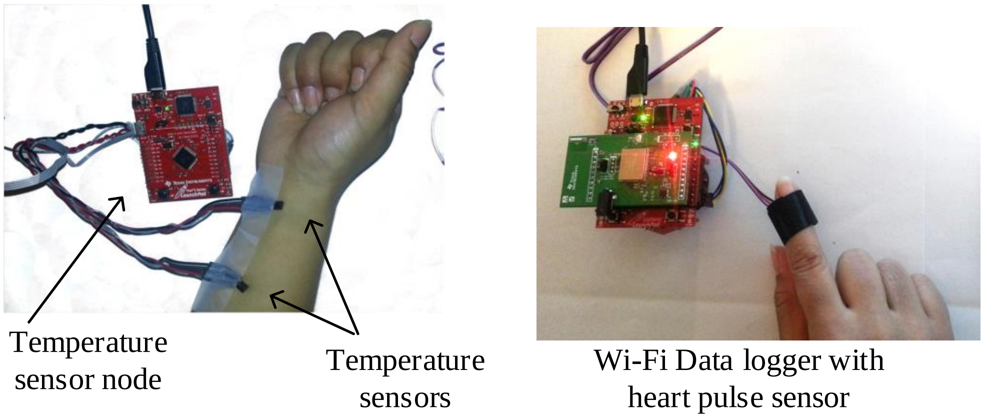


Figure 6-5. Wi-Fi data logger with wireless temperature node and heart pulse sensor.

The heart pulse sensor was connected to a 12-bit ADC pin which sampled analog data at a rate of 125ksps. Real-time heart pulse data was then processed to calculate heart rate per minute. This processed data was then sent to the smartphone for logging and presentation. The temperature sensor was connected using RF sensor node. Two temperature sensors were connected to a single node. It can be extended up to 6 sensor nodes and limited by the number of transmitters supported by RF transceiver.

6.4.1 Results and Discussion

The data logger collected data from both wireless sensor node (temperature sensors) and wired heart pulse rate sensor. The collected data was presented on an Android app and saved on the microSD card in the form of comma separated value (CSV) format for future processing. A snapshot of the Android app showing heart pulse rate and temperature is shown in Figure 6-6. This experiment demonstrates the versatility of the proposed data logger. Using the proposed data logger, we can collect other medical sensor data while capturing wireless capsule endoscopy images.

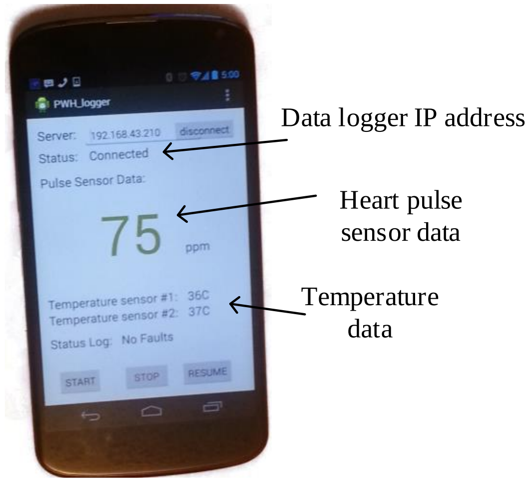


Figure 6-6. Android app showing data from external sensors.

6.5 Comparison with available commercial WCE data loggers

In Table IX, the proposed data logger is compared with several commercial WCE data loggers from MiroCam MR1100, PillCam DR3 and Olympus. The size of commercial data loggers from MiroCam, PillCam and Olympus ranges from 140mm (H) x 85mm (W) x 33mm (L) to 154mm (H) x 87mm (W) x 33mm (L). The size of data logger varies when smart phones or smart devices are used ad data logger. It depends on the type of smart phone used. Usually smart phones are thin and smaller in sized compared to the size of commercial data loggers compared in the Table IX. Commercial data loggers weigh from 350 grams to 500 grams with enclosure and battery. The proposed Wi-Fi data logger (second iteration, PCB fabricated) weighs 120g with battery (excluding enclosure). All three commercial data loggers have non removable and non-expandable memory storage. The memory size and technology in smart device based capsule endoscopy system depends on the type of smart device used. For example, Nexus 4 smart phone used in the experiments had 8GB of microSD card and was expandable up to 16GB. Commercial data loggers do not have remote diagnosis feature. The Wi-Fi data logger enables remote diagnosis by uploading capsule endoscopy data via available networks in smart phone. After capturing data in the smart phone, it can be uploaded to remote cloud (e.g. Dropbox, Onedrive etc.), shared via email, stream to remote applications like http, ftp to enable tele medicine. The battery life of prototype data logger was 40 hours when Wi-Fi is turned off and local data logging is used, When Wi-Fi is used to use smart device as data logger, the battery lasted for 8 hours which is sufficient for a capsule endoscopy session. When smart device is used as data logger, the battery life of smart device depends on the type of smart device used. From the comparisons, it can be seen that the proposed data logger offers the flexibility of using smart devices like Android smartphones and tablets as a data logger. The proposed data logger also is compact in size, lightweight and has a longer battery life compared with other data loggers.

Table IX. Comparison with available commercial WCE data loggers.

Products	**Data logger type and size**	**Data logger Weight (including battery)**	**Storage size, technology**	**Remote diagnosis**	**Mobile platform**	**Battery life of data logger**
MiroCam MR1100	Conventional, 140mm (H) x 85mm (W) x 40mm (L)	350g	-	No	No	12 hrs
PillCam DR3	Conventional, 130mm (H) x 85mm (W) x 37mm (L)	500g	16GB, removable SD	No	No	10 hrs
Olympus	Conventional, 154mm (H) x 87mm (W) x 33mm (L)	390 g	-	No	No	10 hrs
Proposed	Smart-device	Typically 120g^	8GB[1] (expandable)	Yes	Android	40 hrs[2]

[1]Limited by the memory capacity of Android phone while Wi-Fi streaming is enabled; [2]Wi-Fi disabled, data logging only; “- “Not mentioned, ^Without enclosure

CHAPTER 7

SUMMARY AND CONCLUSION

7.1 Summary

The recent development of low power smart mobile devices attracted medical equipment to integrate mobile features in their systems. Some research and development have been conducted to integrate smart devices with medical devices. The main objective of the thesis is to use existing Wi-Fi technology and smart device-based technology for the capsule endoscopy system.

This thesis research has various strengths related to use of smart device in medical applications, using unified device for medical data logging and using mobile devices for capsule endoscopy system. The proposed hardware design and software architecture enables usage of smart devices in medical applications like capsule endoscopy. The proposed hardware provides means of Wi-Fi connectivity to medical sensors like heart rate, temperature and implantable sensors. The proposed hardware and software solution provides flexibility of adding sensors without changes in software and hardware. Any Android based smart phone can be used as medical data logger just by installing an app. This enables flexibility of using smart phones in medical application and avoids using dedicated hardware device for data logging purpose. There are several advantages of using smart phone as data logger. Smart phone has different connectivity options to share data, this enables tele-health and remote diagnosis features. Some smart phone offers expandable memory which is beneficial for data logging application which requires large storage for storing image. In this research, an app is developed for capsule endoscopy application. In vivo and ex vivo experiments showed viability of Wi-Fi based data logger in medical applications.

This thesis research has various study design limitations related to hardware design and testing. The design of data logger did not include isolations and control of leakage current from device. The effect of isolations and leakage currents in wired medical sensors were not investigated in this work. The capsule hardware used in the testing was not small enough for live animal to sallow. Hence capsule hardware was inserted via surgical hole inside pig. The performance of data logger was not validated when capsule hardware was in live motion. The medical data were saved in smart device and later exchanged via email, cloud sharing and other online services. The security of medical data during data exchange was not studied in this work.

This thesis has various technical limitations. One of the limitation is availability of Wi-Fi modules. At the time of writing this thesis, only few Wi-Fi modules were available with TCP/IP stack and small PCB footprint. The option of Wi-Fi module and technology limit the usage of 802.11ac or 82.11b/g/n network. The Wi-Fi module used in the design was not designed to operate as AP mode. This limited the use of smart phone as Wi-Fi hotspot during testing. Another limitation was the use of PCB technology for hardware prototyping. For medical devices, the Association Connecting Electronics industries (IPC) recommends usage of medium density components for PCB. This limits the size of PCB that can be fabricated using selected components. The design of data logger hardware is guided by the wireless capsule developed in the lab of University of Saskatchewan [38]. Since both RF transceivers in capsule hardware and data logger needs to be identical, the RF transceiver selection is limited by the RF transceiver used in the capsule hardware.

The research and development outlined in this thesis is summarized below:

- A low power data logger was designed for use with wireless capsule endoscopy system. It uses Wi-Fi technology to transmit data from a data logger to a smart device and/or PC. Medical data was collected from different medical sensors and transmitted to the smart device for data storage and analysis.

- The proposed device was fabricated and tested with the wireless capsule endoscopy system, and the results showed the capability of developed hardware and software to integrate with the wireless capsule endoscopy system.
- The developed software was tested on the Android platform for both mobile and tablet environments. The result of both devices were similar and showed the capability of current smart devices for handling wireless capsule endoscopy data.
- Both in vivo and ex vivo testing in pig's intestine were conducted to validate the performance of the Wi-Fi based data logger.
- The Wi-Fi based data logger was tested with other sensors to demonstrate the capability of collecting data from different sensors.

7.2 Recommendation for future works

The recommended future works for improving the performance and enhancing features are as follows:

- The Wi-Fi technology can be upgraded to support 802.11 abg/n and ac version of the networks, which provides higher data transfer speed and long range communication.
- The data logger can be customized to support inbuilt Wi-Fi AP so that it all connecting devices can act as clients and private Wi-Fi network can be created for better security.
- The design can be enhanced to minimize the physical size of the device by using circuit components with miniature footprints. The miniature footprint components will not impart performance of data logger as long as they are identical in electrical characteristics like voltage, current, impedance and tolerance.
- The software can be developed for another mobile platform for better support for mobile devices from different vendors for e.g. Apple iOS, Ubuntu mobile OS etc.

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