A Prototype Design of Wireless Capsule Endoscope

By

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ABSTRACT

This thesis studies the challenges and technologies involved in developing a Wireless Capsule Endoscope. Experimental studies were performed to determine the transmission frequency to be used for the wireless link. Four solutions are proposed with one of which built using commercially available technology. The prototype was implemented and verified.

Diseases of the Gastrointestinal (GI) tract, such as intestinal bleeding and ulcer, are very common. The traditional device – enteroscope, which makes use of fiber optics for light and video transmission, are used for GI tract diagnosis. However, not only does the enteroscope creates patient's discomfort, the device fails to diagnose diseases at the small intestine, especially the duodenum as this region is out of reach by this device.

Wireless Capsule Endoscopy is a state-of-the-art device which shows promising results when comparing with the existing endoscopy tests, while at the same time reduces patient's discomfort. It is sealed in a capsule with the size of a vitamin pill. Once swallowed, it takes pictures of the GI tract and transmits them out of the human body wirelessly. However, the device under used still has plenty of rooms for improvement. Quite a few research groups, including us, around the world have been working on the

device's control and movement, as well as more effective video transmission from the capsule to outside the human body. Therefore my research was to investigate the current technologies and build a prototype which served as a platform for future development.

The core function of the Wireless Capsule Endoscope was wireless video transmission from inside to outside the human body. The frequency of wireless transmission became the determined factor to decide which technology to use. Therefore Part I of this thesis presents an experimental study conducted to investigate the effect of human body attenuation for radio waves at different frequencies spanning 100MHz to 6GHz. A radiating source was placed inside an experimental model of a human body trunk, and a receiving antenna was placed right in front of the model. By varying the frequency of radiating source, the power strength of the radiation received outside the model was recorded. It was found that the higher the frequency, the more the energy was absorbed by the body trunk model. From this experiment, it was concluded that the 434MHz, 915MHz and 2.45GHz ISM bands could be used for Wireless Capsule Endoscopy.

Part II presents the prototype design and implementation of the device. Different technologies for the wireless video transmission were discussed. Analog modules are generally bulky but easy to implement, while digital modules are small in size but complex. Out of the four proposed solutions, the simplest solution using analog modules was implemented. A 1/4" CMOS analog camera and a TV modulator chip, Motorola MC44BC373 formed the core of the device. It was programmed to transmit at frequency of 800MHz. A coil antenna was tuned to radiate at this frequency and a lighting system consisting of four white LEDs were built. The resulting circuit was packaged in a circular plastic case with a transparent dome and pushed inside a porcine colon in vitro. A straight TV antenna was placed at a distance of 5cm from the colon to pick up the video transmitted from the device, and the video was displayed on a traditional TV. The function of the prototype was verified by viewing the motion pictures that the prototype captured inside the porcine colon on the TV.

摘要

本論文探討研發無線膠囊內窺鏡所面對的困難和挑戰，與及種種可行的方案。我們進行了一個實驗來決定應該用甚麼頻率作無線傳輸。在本論文提出的四個方案當中，我們選了其中一個並建立了原型。

消化道疾病如出血、潰瘍等是非常普遍的。傳統的診斷工具內窺鏡一般都以光纖作光和影像傳送。可是，這些傳統的內窺鏡除了會引起病人不適外，還因爲它的靈活性有限，未能到達消化道中的小腸，尤其是十二指腸的位置，因此它還有很多不足之處。

無線膠囊內窺鏡是目前最前沿的設備。它除了能夠媲美傳統的內窺鏡外，還可以減輕病人的不適。這設備用一個維他命丸大小的膠囊封著，讓病人從口中吞下去，它便把消化道中的情況拍下照片並利用無線傳輸把照片傳到病人體外去。雖然這設備比傳統的內窺鏡有很大的突破，但是它還有很多可以改進的空間。在世界各地也有一些研究組，包括我們，在研究可以改進的地方，例如膠囊的活動控制、有效的影像傳輸等。因此，我的研究就是要探討怎樣用現在的科技去製作一個無線膠囊內窺鏡的原型，作爲一個研究平台。

無線膠囊內窺鏡的主要功能是無線影像傳輸，即利用無線技術把影像從人體內的膠囊傳到人體外去。而無線傳輸所用的頻率則決定了整個傳輸系統的設計。因此，本論文的第一部分，我們設計了一個實驗來調查人體對不同頻率的無線電波

的影響，範圍為１００MHｚ至６GHｚ。我們把一個放射器放在一個仿人體的實驗模型中，然後把接收天線放在模型前面。我們調校放射器的頻率，再把接收器收到的訊号強度記下來。我們發現，頻率越高，實驗模型就會吸收越多的放射能量，而接收器收到的訊号則越弱。從這實驗結果得知４３４MHｚ，９１５MHｚ和２．４５GHｚ的「工業、科學、醫療」頻道（ISM　Bands）均可用作無線膠囊內窺鏡的原型設計。

本論文的第二部分是原型的設計。我們探討了市面上可以買到的科技產品，及它們如何能應用在原型設計上。我們提出了四個設計方案，並選了其中一個方案來開發。此原型包含一個四分一寸的互補金屬氧化物半導體（CMOS）的模擬照相機，及摩托羅拉的電視調節器晶片作為傳輸器。這晶片用程式控制以８００MHｚ作無線傳輸，再加上一個調校至此頻率的線圈天線，以及四顆白色發光二極管組成的系統作照明。整個電路被放在一３２mm（直徑）ｘ４５mm（長）的透明膠囊內，再把膠囊放進清洗乾淨的豬的大腸裡。為了驗證此系統的功能，我們把一條電視的直天線放在距離大腸５ｃm的位置接收影像，再用一個普通的電視機把影像顯示出來。

總括而言，我們成功研發了一個無線膠囊內窺鏡原型並對此技術的種種挑戰和發展有更深的了解。

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Chapter 1 Introduction

1.1 Diseases of the Gastrointestinal (GI) Tract

The Gastrointestinal (GI) tract, as shown in Figure 1-1, is a 30 feet long structure which includes the esophagus, stomach, intestine and colon. Diseases of the GI tract, such as intestinal bleeding and ulcer, are very common. In order to determine the location of the disease, as well as to diagnose the problem, Gastroscopy and Colonoscopy tests are usually performed. The traditional device – Push Endoscope used in these tests makes use of fiber optics for light and video transmission. It equips with a camera and a control unit so that video images of the GI tract can be sent through a cable to a monitor outside the patient for display. While a Gastroscope is pushed through the patient's mouth to examine the first 4 feet of the GI tract and a Colonoscope is pushed through the patient's anus to examine the bottom 6 feet of the tract, the remaining 20 feet of the tract is out of reach. Other imaging and diagnostic techniques for GI tract diseases such as CT scan or MRI and X-rays are neither accurate nor effective. Gastroscopy and Colonoscopy also create patient discomfort because the devices are pushed through the patient's mouth and anus. Figure 1-2 shows illustrations of Gastroscopy and Colonoscopy tests.

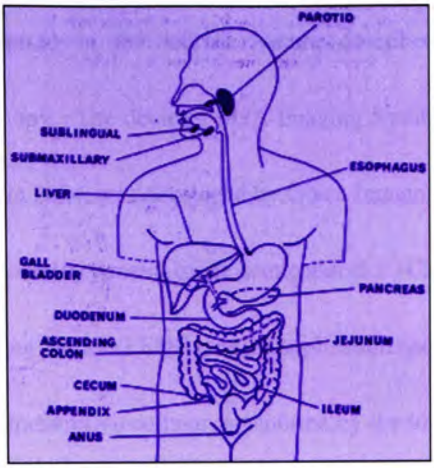

Figure 1-1 Human Gastrointestinal (GI) tract [1]

Figure 1-2 Graphical illustration of Gastroscopy (left) and Colonoscopy (right) [1]

1.2 Wireless Capsule Endoscopy

Wireless Capsule Endoscopy, as its name describes, is an endoscope concealed in a capsule. When swallowed, it will travel through the GI tract and transmit wirelessly images of the GI tract, which are taken by its equipped camera. In May of 2000, a short paper [2] appeared in the journal Nature described this new form of gastrointestinal endoscopy. The device - M2A Imaging System, which was given a new name of PillCam in 2004, was developed by Given Imaging, Atlanta, GA. [3]-[6] It consists of a complementary metal oxide semiconductor (CMOS) image sensor, a lens, white light emitting diodes (LEDs), and an application specific integrated circuit (ASIC) transmitter to transmit video images captured by the image sensor wirelessly. The size of the capsule is 11mm in diameter and 25mm in length. Figures 1-3 and 1-4 show the size and composition of an M2A capsule. Once the M2A capsule is swallowed, it will travel through the whole GI tract by peristalsis. It will keep capturing images of the GI tract and transmit them out of the body to a portable receiver at a frequency of 433MHz until the battery dries out in 6-8 hours. The M2A capsule is FDA approved and is getting acceptance in developed countries.

Figure 1-3 The M2A capsule developed by Given Imaging [6]

Figure 1-4 Composition of the M2A capsule: 1-Optical dome; 2-Lens holder; 3-Lens; 4-Illunimating LEDs; 5-CMOS imager; 6-Battery;7-Transmitter; 8-Antenna [6]

A lot of studies [7]-[17] have been done to investigate its effect in treating different diseases such as gastrointestinal bleeding [7][8][10]-[12], Crohn's disease [14][15] and inflammatory bowel disease [9][13][17], compared with different diagnostic techniques including push enteroscopy [7]-[10] and small bowel radiography [13]. All of the studies found the technology promising and efficient. The pilot study performed by Lewis and Swain [12] demonstrated that wireless capsule endoscopy provided excellent visualization of the small intestine, was well tolerated by patients, and was safe. It identified small intestinal bleeding sites beyond the range of push enteroscopy. The study of Crohn's disease diagnosis [15] concluded that wireless capsule endoscopy diagnosed Crohn's disease of the small bowel with a diagnostic yield of 71%. It was demonstrated as being an effective modality for diagnosing patients with suspected Crohn's disease undetected by conventional diagnostic methodologies. Lewis and Swain [12] compared capsule endoscopy to push enteroscopy with obscure gastrointestinal bleeding and found that both techniques had a similar rate for discovering lesions (35% & 30% respectively). Study of capsule endoscopy as compared with small bowel radiography [13] found that capsule endoscopy successfully diagnosed 45% of cases which had Crohn's disease, angiectasia and small bowel polyps, while small bowel radiography diagnosed only 15% of the case.

Although clinical findings of the M2A capsule are promising, there are still a lot of rooms for improvement. First of all, the M2A capsule moves passively in the GI tract. In another words, it does not have an actuator but moves only by peristalsis of the tract. As a result, while the capsule is traveling inside the tract, a lot of time is spent not at the spots of interest. In addition, the capsule cannot control itself to always have its front end heading the journey, and therefore there is a great chance of missing the disease spots. Hence, developing a capsule that has the ability to actuate itself - speed up or slow down its travel in the GI tract, and stop at the spots of interest when desired - is at the top of the list. Having no therapeutic ability is another draw back of the system. Although the M2A capsule showed promising result when compared with other diagnostic devices, it cannot cure the bleeding or remove the polyps at the spots where they are found, as compared to enteroscopy. Therefore, designing a wireless capsule endoscope which equips with the ability to perform minor operation or medication is another big topic in the priority list.

After the appearance of the M2A capsule, research groups such as the RF System Lab Company of Japan [18], Olympus, Japan [19], Intelligent Microsystem Center, Korea [20], C.A. Mosse et al [21], H. J. Park et al [22][23] and X. Xie et al [24] have been working on the system, hoping to further improve the system in terms of video transmission, control and movement.

RF System Lab is working on the Norika System [25], with the concept design showing in Figure 1-5. Instead of using a CMOS camera as in the M2A capsule, Norika is designed to have a charge-coupled device (CCD) camera, which has better resolution but consumes more power. In addition, the Norika system will have a wireless control unit, so that an operator will be able to control the capsule's movement. Furthermore, the system will be equipped with two tanks, one of which for tissue sampling and another for spray medication. With these tanks in place, the capsule will be able to perform more powerful diagnosis as well as therapeutic functions. The Norika capsule is designed to power itself through magnetic inductance and therefore no battery is needed. The system is still in its development stage and not anywhere close to mass production.

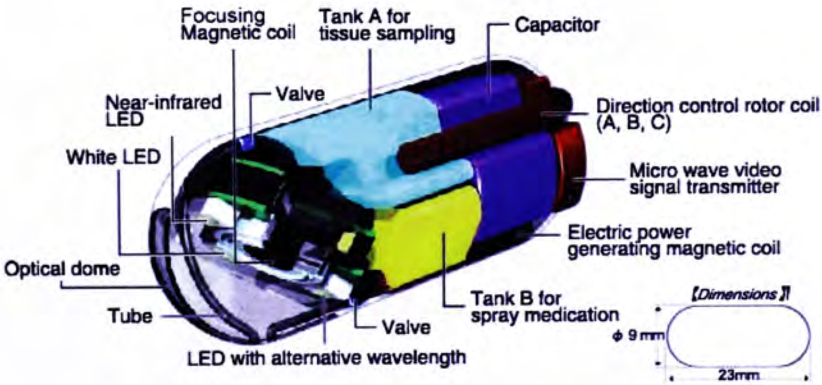

Figure 1-5 Overview of the Norika system [25]

Intelligent Microsystem Center (IMC) from Korea and Olympus from Japan developed MiRo #1 and Passive Capsule Observation Endoscope respectively, which are similar to the M2A capsule. IMC is planning to commercialize the device in Korea at the end of the year and Olympus has initiated clinical trials in Fall of 2004. Both IMC and Olympus are currently working to improve the device so that it can move actively in the GI tract. The conceptual diagram of future designs from IMC and Olympus are shown in Figure 1-6 and 1-7.

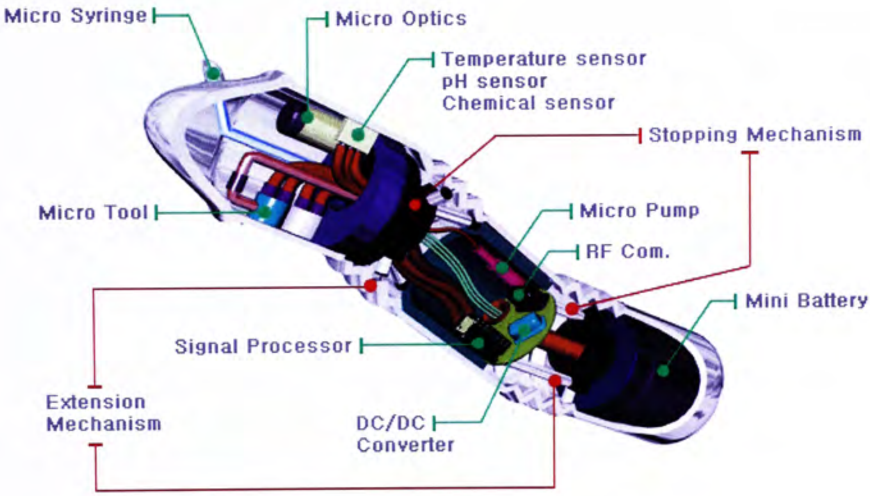

Figure 1-6 Overview of the MiCo #1 system [20]

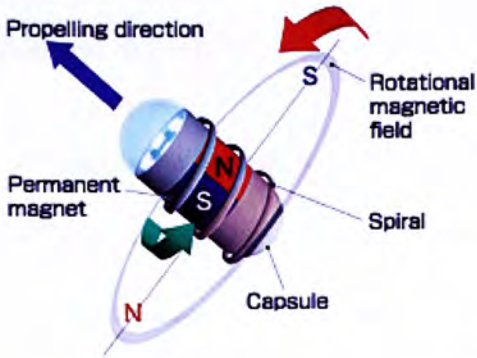

Figure 1-7 Overview of the Olympus system [19]

C. A. Mosse et al [21] investigated the application of electrical stimulation at the small intestine to propel the endoscope. By stimulating muscular contraction at the small intestine, local contraction causes the capsule to move forward. H. J. Park et al developed a bi-directional telemetry module for wireless endoscopy, enabling a 2-way communication between the capsule and the operator [22]. The capsule was able to receive comments wirelessly so that it can be commanded to turn off the LEDs and camera when it is not at the spots of interest. The group later fabricated a locomotive mechanism for the capsule using shape memory alloys (SMAs) [23]. The mechanism imitated the locomotion of insects and in-vitro tests were done. X. Xie et al. designed a low power IC that could be use for the wireless capsule endoscopy system [24]. The IC integrated a central processing unit (CPU) and the wireless transmission module into a single chip. No actual experiment has been performed to verify the function of the IC, however.

1.3 Goals of My Research Project

Although the M2A Imaging System has been widely accepted by many developed countries, there is still plenty of room for improvement. The goal of our research group, which is headed by Professor Max M.-Q. Meng, is to develop our own intellectual property, as well as to provide a cheaper solution for the China market. Being a member of the research group, my project was to evaluate the challenges and technologies involved in designing the system, and to develop a prototype of the Wireless Capsule Endoscope which was able to capture video of the GI tract and transmit the images wirelessly to an external monitor. The prototype would then serve as a platform for further development and additional functions.

While the M2A capsule has all the components custom made, my research was to build a similar device using commercially available technologies. This thesis provides a deep analysis of current technologies and their application to Wireless Capsule Endoscopy. Since the choice of technologies is affected by many factors, including cost, size and their effects on the patient who will be using this device, studies have to be conducted to determine the interaction of the device with the human body. As the main function of the prototype is wireless video transmission, the choice of frequency for wireless transmission affects the design completely. As a result, fundamental research of choosing the right transmission frequency was conducted, from which a prototype could be designed.

This thesis is divided into two parts. Part I investigates the relationship between wireless transmission frequency and the human body attenuation, which forms a basis to the actual prototype design in Part II.

PART I – EXPERIMENTAL STUDY TO DETERMINE THE FREQUENCY OF WIRELESS TRANSMISSION

Chapter 2 Background

2.1 Analog and Digital Wireless Video Transmission

Because of the rich information provided by video images, the bandwidth of an analog video is at least 6MHz, and the data rate of a digital video is at least 3.5Mbps for a 2 frames per second (fps) system with CIF (352x228) resolution. Therefore, transmitters for video transmission have to be specially designed for this high volume of data. For analog video transmission, frequency above 30MHz should be use in order to embed to 6MHz video bandwidth. Uncompressed digital video transmission requires higher transmission frequency than analog video because of its high data rate. Typical transmission frequency is 2.4GHz. These frequencies are in the Very High Frequency (VHF), Ultra High Frequency (UHF) and the Microwave frequencies range.

2.2 Industrial, Scientific and Medical (ISM) Bands

Another factor affecting the choice of frequency is regulation. The use of frequencies is bounded by the regulation of local authorities, such as the United State's Federal

Communications Commission (FCC), and the Hong Kong's Office of the Telecommunications Authority (OFTA). The allocation of radio frequency (RF) bands or spectrums is similar world-wide but subject to change by local authorities. For instance, OFTA follows FCC closely for frequency allocation. In North America and in Hong Kong, the FCC and OFTA have allocated unlicensed radio spectrums for general use. These spectrums are known as the Industrial, Scientific and Medical (ISM) bands. Table 2-1 lists the ISM bands that are of interest to our application, allocated by FCC and OFTA.

Table 2-1 ISM Bands allocated by FCC and OFTA

ISM band	**Center Frequency**
40.66 – 40.70 MHz	40.68 MHz
433.05 – 434.79 MHz	433.92 MHz
902 – 928 MHz	915 MHz
2.4 – 2.5 GHz	2.45 GHz
5.725 – 5.875 GHz	5.8 GHz

2.3 Adsorption of RF Energy by Biological Tissue

Since video transmission requires a wide transmission bandwidth because of its information capacity, UHF and microwave frequencies have to be used as the wireless link. However, the electrical properties of biological tissues, namely conductivity and permittivity, are frequency dependent. Because of the high water content of body tissue, it is found that the absorption of electromagnetic power increases with frequency [26]-[29]. This not only generates potential hazards to the human body, but also lowers the power available at the receiving end. As a result, higher sensitivity receiver has to be designed, if the power is high enough to be received at all. Chirwa et al [30] found that at frequency above 1GHz, the radiation field falls rapidly, which means the radiation transmission becomes less effective, and may not be suitable to use. A lot of research has also been done to determine the electrical properties of individual body tissue, such as blood, muscle, fat and skin [31]-[35]. All of these findings gave a general trend of increasing adsorption with frequency, with the amount of adsorption depending on the amount of water content in the tissue.

2.4 Frequency used by Implanted/Ingested Devices

Up to now, all the implanted or ingested devices use frequency of less than 1GHz as the wireless links. Recently, with the development of Frequency Modulation (FM) technology and the use of VHF and UHF spectrums for television broadcasting, a few of medical devices were developed to make use of these frequencies [2][27][34]. The M2A Imaging System has a 434MHz RF transmission system for images or video transmission from the capsule to the receiver wore by the patient. Although it is the rule of thumb to design a biotelemetry system of less than 1GHz, an integrated circuit (IC) design of Wireless Capsule Endoscopy proposed by Xie et al [24] used 2.4GHz as the RF frequency.

2.5 Incentives of using Higher Frequencies

Despite the fact that adsorption of RF energy increases with frequency, there are still a lot of incentives for using higher frequencies for wireless transmission. RF components, such as antenna, mixer and amplifier, usually have size comparable to the wavelength of their operating frequencies for efficient operation. For example, a dipole antenna of 300MHz is half its wavelength, which is half a meter long. When antennas and related RF components shrink, their performance drops. According to Scanlon et al [27][35], a 418MHz source with a multiturn loop antenna has conversion efficiency (from dc to radiated RF power) of 0.006%, which corresponds to -42dB of loss. As a result, higher transmission frequency allows the use of smaller antennas and electronic components, which is an important advantage for ingested or implanted sources.

With the advanced of internet and wireless technologies, a lot of work has been made to develop components in the 2.4GHz range. These include the use of wireless local area network (WLAN) and the Bluetooth technology. This gives another incentive for using frequency of above 1GHz.

2.6 Radiation Efficiency from an Implanted/Ingested Source

As mentioned in Section 2.3, a lot of work has been done to investigate the relationship between frequency and biological tissue absorption of RF energy. Nevertheless, the human body is composed of various body tissues in a very complicated manner. It is very difficult to predict the absorption of electromagnetic power radiated from an ingested or implanted source by the human body. Some computation techniques [36] and average specific absorption rate (SAR) determination experiments [37]-[42] performed on animals [37] were introduced.

Although quite a few investigation have been performed to determine the effect of human body on radiated field, almost all of these studies have been based on external sources [37]-[45]. Most of which [39]-[44] were concerning handset antenna and human body interaction instead of implanted or ingested source. Until recently, implanted source has been studied in realistic human models [30][35]. In these studies, Scanlon et al [35] described the experimental measurement and electromagnetic modeling of propagation from 418MHz and 916.5MHz sources placed in the human vagina. It was found that greater loss was encountered at 916.5MHz, with net body loss ranging between 23.4 and 24.4dB, while loss at 416MHz was between 14.7 and 18dB. The study performed by Chirwa et al [30] used a Finite Difference Time Domain (FDTD) mesh of a human subject, which was created using digitized data in the Visible Human Project [46], to simulate the effect of human body of an ingested source positioned at different locations in the GI tract at frequency ranging from 150MHz to 1.2GHz. Simulation result showed that the maximum radiation occurred between 450 and 900MHz. Although this range covers the two ISM bands: 434MHz and 915MHz, these bands are not well developed for digital video transmission. As digital devices are decreasing in size, the incentive of using digital video transmission increases. At higher frequencies such as 2.45GHz and 5.8GHz, video transmission is better developed for WLAN and Bluetooth application.

In conclusion, studies by Scanlon et al and Chirwa et al were the only studies concerning an implanted or ingested source, with frequency range from 150MHz to 1.2GHz, not covering the whole range of interest in this application. Therefore, a fundamental research was needed to further investigate the effect of human body attenuation at a wider range of frequency, from an ingested source, using a realistic model as compared with Chirwa et al's computer model.

As a result, the experimental study was designed to investigate the absorption or attenuation of human body from an ingested source, covering the frequency of 100MHz to 6GHz, using a simplified experimental model. Having in mind that attenuation of human body is different for different people, due to different body size and tissue composition, this study aims to give an estimated value that will serve as a reference for future biotelemetry design.

Chapter 3 Material and Method

3.1 Human Body Trunk Experimental Model

A simplified experimental model was built to simulate the human body trunk. With reference to the anthropometry data of an average man [47], a rectangular tank made of acrylic sheet (Polymethyl methacrylate or PMMA) of 4mm thick, was made to a size of $55x24x16cm^3$, with each of the dimensions corresponded to the shoulder height, breath and depth of a human body trunk respectively. Figure 3-1 shows the corresponding dimension of the model.

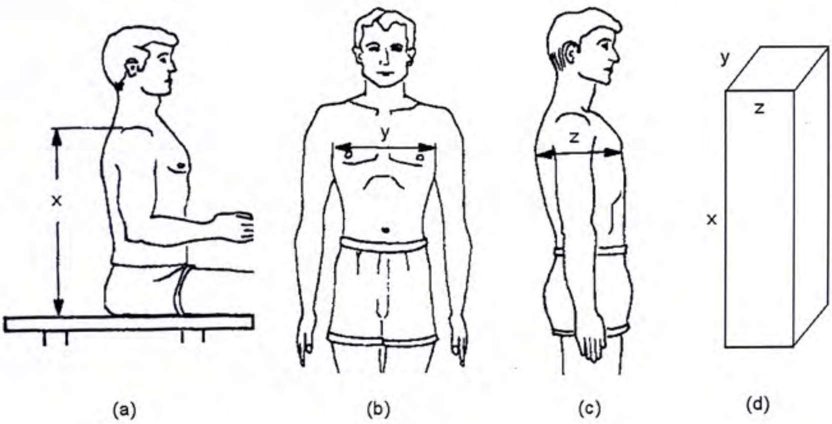

Figure 3-1 (a) Shoulder height, (b) chest breath, (c) chest depth, (d) Simplified experimental model of human body trunk with dimensions corresponding to the average human body size

3.2 Radiating and Receiving Antennas

Patch antennas made of 0.8mm FR4 were used as radiating sources inside the model to simulate an internal source in human body or in the GI tract. Five patch antennas matched at frequencies of 300MHz, 900MHz, 1.5MHz, 3.0GHz and 4.8GHz were used to cover the frequency range of the experiment. Each of them was placed inside a sealed 9.5x7.5x4.5cm^3 case made of Polypropylene Plastic, which was placed in the center position of the model. The antenna was then connected to a signal generator via an RG-317 cable. A broad-band yagi antenna and a broad-band horn antenna were used as the receiving antennas for the frequency range of 100MHz – 1.3GHz and 1.5GHz – 6GHz respectively. The receiving antenna was placed in front of the model and was connected to a spectrum analyzer to display the receiving power. Fig. 3-2 shows the complete setup without (a) and with (b) the receiving antenna.

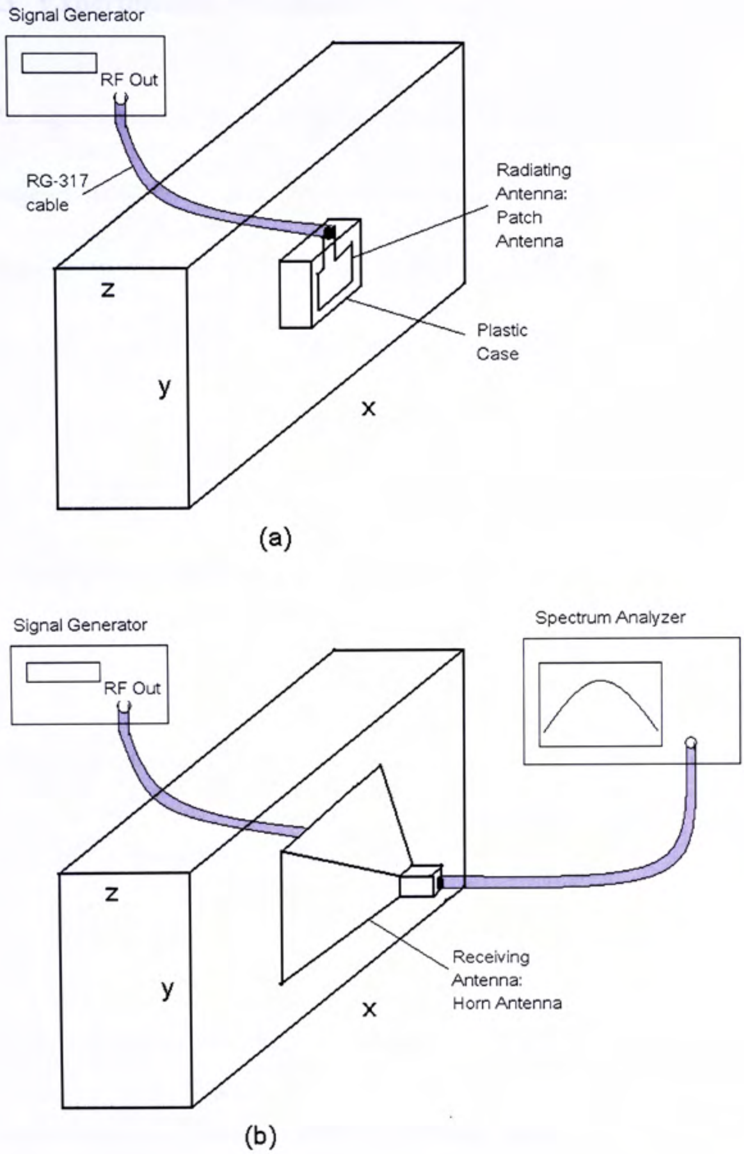

Figure 3-2 (a) Experimental setup without showing the receiving antenna, (b) The whole experimental setup

3.3 Experimental Procedures

The signal generator produced an RF signal at 18 different frequencies, spanning the range of 100MHz – 6GHz. With the receiving antenna connected to the spectrum analyzer, the received power in dBm at each of the frequencies was recorded as the receiving power in air, $P_{r,air}$. Then the tank was filled with 20L of distilled water and 20L of 0.9% NaCl saline solution alternately and the received power was recorded as $P_{r,water}$ and $P_{r,saline}$. With these values recorded, attenuation of different water and saline solution in this setup is represented by

$$\text{Attenuation of water in dB} = P_{r,air} - P_{r,water}$$

$$\text{Attenuation of saline in dB} = P_{r,air} - P_{r,saline}$$

assuming that attenuation of air is negligible.

In order to estimate the attenuation of body tissue, porcine body tissue was used. Two layers of porcine tissue cutting from the chest and abdomen of an adult pig were used to embed the plastic case to simulate the chest, abdomen and back of a human trunk. The layers of porcine tissue included skin, fat, muscle and rib bones, which served as a realistic model of the human chest and abdomen wall. Each layer of porcine tissue was about 5cm think and weighted 4kg. After the porcine tissue was placed in the tank embedding the plastic case, the empty space of the tank was filled with 12.5L of saline solution. Received power in dBm was then recorded as $P_{r,tissue}$ and attenuation of porcine tissue is represented by

Attenuation of porcine tissue in dB = $P_{r,air} - P_{r,tissue}$

The above procedures were repeated for each of the patch antennas.

In this setup, a lot of factors affecting radiation and transmission of RF frequencies could be ignored. Since the attenuation of a specific material was taken as the receiving power with the material *relative* to the receiving power without the material, factors such as antenna orientation, antenna gain, attenuation of RG-317 cable and the tank, as well as the effect of antenna mismatch would be cancelled out. Therefore, although the five patch antennas used in this experiment were matched at five specific frequencies, they were used for the whole frequency range. The experiment was conducted at 20°C.

Chapter 4 Results and Discussions

Five sets of data were collected from the five patch antennas. The values were then averaged and tabulated in Table 4-1. The standard deviation was quite large at high frequencies. At these frequencies, attenuation became very large and the spectrum analyzer was less sensitive to receiving power. The averaged values were plotted in Figure 4-1.

Table 4-1 Attenuation of water, saline and porcine tissue from 100MHz to 6GHz

Frequency (GHz)	Water Attenuation (dB)		Saline Attenuation (dB)		Tissue Attenuation (dB)	
	Average	SD	Average	SD	Average	SD
0.1	1.83	1.26	7.50	0.50	4.50	3.28
0.2	3.17	1.44	8.50	2.78	9.00	6.14
0.3	2.40	2.27	10.60	2.22	12.90	3.34
0.4	3.17	1.26	17.75	1.06	13.90	3.70
0.5	3.30	2.05	12.40	2.04	6.10	3.21
0.6	3.25	0.96	14.88	3.42	12.00	3.65
0.7	4.81	1.10	13.60	2.33	15.80	2.56
0.9	5.81	2.09	21.20	1.92	16.10	2.16
1.3	13.88	0.99	33.60	1.78	22.30	1.10
1.5	13.63	2.05	30.30	3.03	24.70	1.25
2.0	18.63	2.08	37.00	3.06	33.90	1.39
2.4	20.67	9.28	33.50	8.30	32.75	6.44
2.8	30.88	9.48	48.00	6.36	37.50	5.68
3.2	31.56	5.39	46.30	7.82	42.30	8.37
3.8	36.75	6.54	48.17	2.57	45.60	6.96
4.5	47.43	9.77	55.80	16.70	53.38	12.15
5.3	46.43	11.08	56.10	3.56	56.50	2.18
6.0	55.13	15.38	59.60	5.02	56.80	3.40

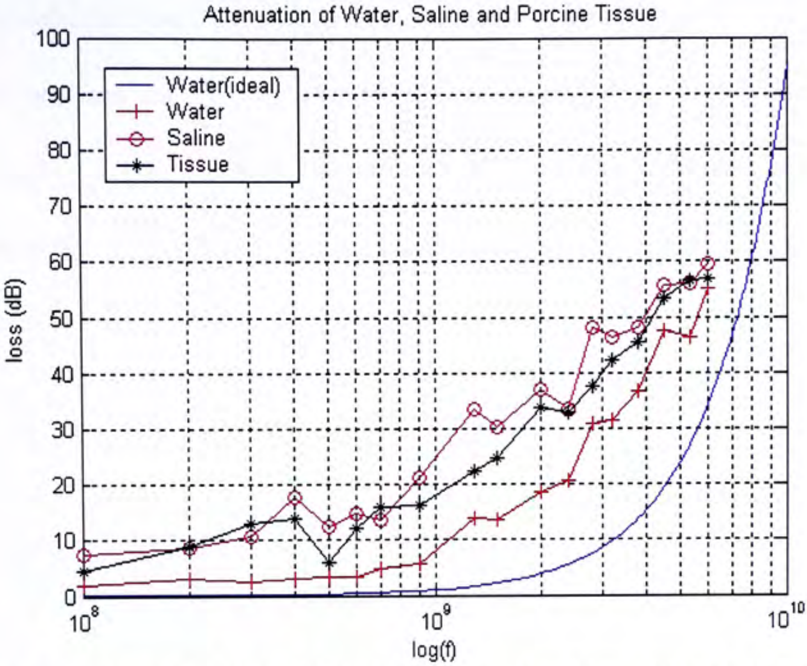

Figure 4-1 Attenuation of Water, Saline and Porcine Tissue from 100MHz to 6GHz

In this figure, an ideal curve of attenuation when plane wave travels through 6cm of water is provided for reference. This curve was calculated using Debye equation [48]

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (\omega \tau_d)^2} \quad ; \quad \sigma = \frac{\omega^2 \tau_d [\varepsilon_0 - \varepsilon_\infty]}{1 + (\omega \tau_d)^2} \quad \text{(s/m)}$$

to calculate the dielectric constant ε and conductivity σ of water at 20°C, where ε_0

is the dielectric constant at dc, ε_∞ is the high-frequency dielectric constant, ω is 2 π times frequency, and τ_d is the relaxation time. In the calculation, values measured by Collie et al [49] were used such that ε_0= 74, ε_∞= 5.5 and τ_d =9.55x10e-12s. From ε and σ, attenuation constant α of plane-wave traveling through water can be calculated using

$$\alpha = \omega \left\{ \frac{\mu\varepsilon}{2} \left[\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon} \right)^2} - 1 \right] \right\}^{\frac{1}{2}} \text{ (Np/m)} \quad [50]$$

The power loss in dB is given by $20\log\left(e^{-\alpha z}\right)$ [50], where z is the thickness of water which is 6cm in this case. Note that this "ideal" curve was calculated for plane wave travelling through a plane of water, while in this experiment, the source is a point source embedded in different materials as illustrated in Figure 4-2. Therefore the ideal curve serves as a reference only and was not used for error calculation.

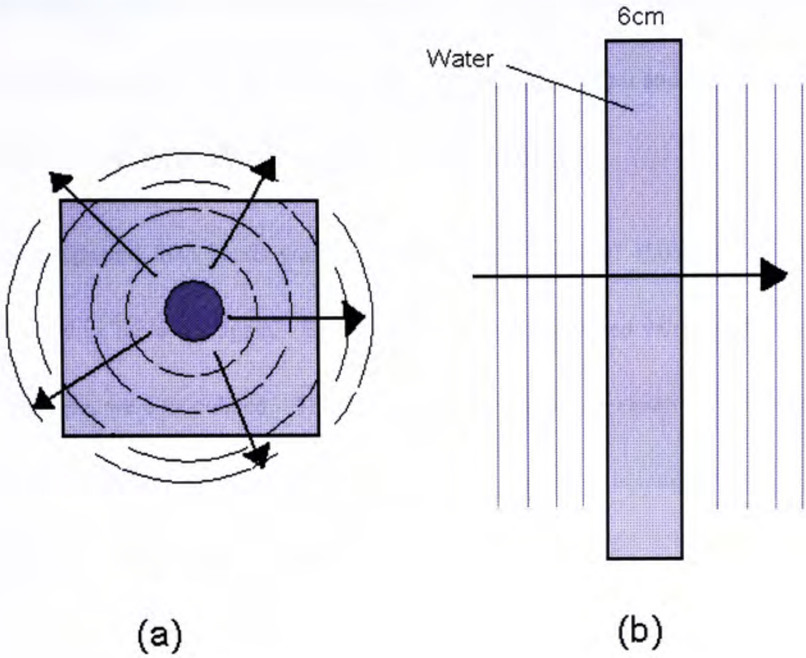

Figure 4-2. Illustration of (a) an embedded source radiating through a material in all direction. (b) plane wave radiating through a plane of water of 6cm thick.

The curves in Figure 4-1 show similar trend of attenuation for water, saline and porcine tissue. The overall trend of all three curves agrees with the ideal curve too. Since the ideal curve is attenuation of water in one dimension only, it is expected that the attenuation of an embedded source would have greater values, and the result followed this analysis too. The experimental data were reasonable and reliable.

Saline solution had higher attenuation than water in the order of 5-15dB. This was expected because saline has higher conductivity and its loss is expected to be greater.

The porcine tissue curve lies between the water curve and saline curve, and it shows a slight drop at 500MHz. This agrees with Chirwa et al [30] that attenuation of human body was slightly lowered at frequency of 400-900MHz.

The designated ISM bands world-wide [51] in the range of 100MHz – 6GHz are tabulated in Table 4-2 again. By interpolation, their estimated values of body tissue attenuation were calculated. The attenuation data from the experimental study that Scanlon et al. [35] performed, which had a source implanted in human vagina, is also included in the table for comparison.

Table 4-2 Estimated attenuation of ISM bands from 100MHz to 6GHz

ISM band	**Center Frequency**	**Attenuation (dB)**	
		Experimental Study at 20oC	**Source for human virginal placement (Scanlon et al., 2000) [35], at 37oC**
433.05 – 434.79 MHz	433.92 MHz	10.78	14.7 - 18
902 – 928 MHz	915 MHz	16.49	23.4 - 24.4
2.4 – 2.5 GHz	2.45 GHz	37.5	
5.725 – 5.875 GHz	5.8 GHz	57.53	

When comparing the result to data obtained by Scanlon et al., the experimental data has lower attenuation values. In the experimental study, only the human body trunk was considered, while the effect of the peripherals, such as arms, legs and heads were not taken into account when designing the model. Since the peripherals will also absorb radiation energy, the resulting data are expected to have lower values. In addition, the experiment was performed in 20°C while Scanlon et al. performed their study at human body temperature of 37°C, and that helps account for the difference. In general, temperature coefficient of the conductivity for biological materials has a maximum value of about 2% per °C for tissues with higher water content [26] and specifically, 0.9% saline has temperature coefficient of 1.6% and 1.3% per °C [52] at frequency of 400MHz and 900MHz respectively. As a result, the attenuation of this experiment is expected to be higher if the experiment is conducted at 37°C.

Although most of the biotelemetry devices chose 434MHz as the wireless link, this experimental result shows that 915MHz and 2.45GHz are also feasible for implanted or ingestible telemetry devices. Typical low range telemetry devices emits radiation power of less than a few milliwatts or dBm [22][24][30], so that the body tissue specific absorption rate (SAR) are well below the IEEE safety limit of 0.4Wkg-1 [53]. At the receiving end outside the body, a typical receiver has operational sensitivity of -80 to -110dBm [7][9]. As a result, the whole telemetry system has about 80 – 110dB of room for loss in system efficiency and body tissue attenuation. 915MHz and 2.45GHz are therefore reasonable choices for biotelemetry devices. Although attenuation at 5.8GHz is within the range, great care must be taken to design a very efficient telemetry system in order to minimize any additional losses.

Chapter 5 Conclusions

With the growth in wireless LAN and Bluetooth technology, miniaturized antennas, camera modules, and other RF devices have been developed for the 2.45GHz ISB band. As the result shows that 2.45GHz is a feasible choice for wireless link, we can make use of these advanced technologies and employ them in biomedical ingested or implanted devices, in addition to the two lower ISM bands, namely 434MHz and 915MHz. At this frequency, digital video transmission of wireless capsule endoscopy application is made possible and easy. Furthermore, biomedical devices of this frequency can be connected directly to the wireless LAN or any wireless monitoring network to enable real-time monitoring or remote control of these devices.

This experimental study gives a reference of attenuation values of a human body trunk of average size using a realistic experimental model. It should be noted that the attenuation values can be different for different body size and different body composition, and therefore the values in this thesis serves as a reference only. Further experiments can be conducted by varying parameters of the experimental model such as temperature, dimension and volume of porcine tissue to be used to determine the effect of body size and body composition in RF transmission.

PART II – PROTOTYPE DESIGN AND IMPLEMENTATION

Chapter 6 Background

6.1 Prototype Overview

The prototype shown in Figure 6-1 has four key components: (1) a video camera, (2) an RF modulator, (3) an antenna, and (4) a lighting system. Once the power of the device is turned on, the video camera will start taking video images of the GI tract.

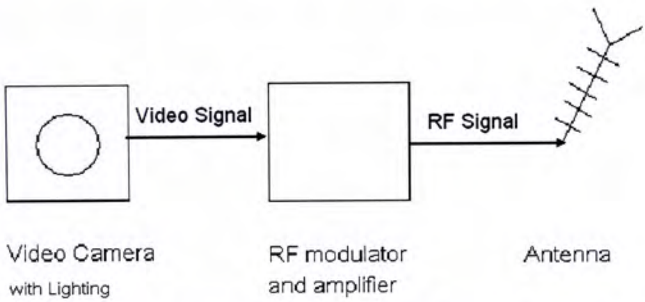

Figure 6-1 Prototype design of Wireless Capsule Endoscope, which includes (1) a video camera, (2) an RF modulator, (3) an antenna, and (4) a lighting system

The video signal will then be processed and up converted into an RF signal by the RF modulator. This signal is then transmitted wirelessly out of the human body through an antenna. Finally, the lighting system is in place to illuminate the interior of the GI tract so that the video camera will be able to capture clear images with suitable brightness.

When designing the prototype, a main constraint was considered - size. The M2A capsule has a size of 11x25mm and the design should not be anything bigger.

6.2 Digital and Analog Cameras

Traditional video is in the form of analog video. This includes the broadcasting television (TV) and the video home system (VHS). On the other hand, digital video has evolved due to better quality and accuracy, with products including video compact disc (VCD), digital versatile disc (DVD) and high definition TV (HDTV).

With the development of CMOS and charge coupled device (CCD) image sensors, the size of both analog and digital camera modules has decreased drastically. While analog cameras are used for applications such as surveillance cameras, which require less precision, digital cameras are mostly developed to meet the demand of digital camera and cell phone camera applications. The CMOS analog image sensor OV7910 developed by OmniVision Technologies, Inc. has a size of 14 x 14mm. Figure 6-2 shows a picture of an image sensor. When a case and a lens are included, the camera module size increases to 20 x 20mm, as shown in Figure 6-3, and this is already the smallest analog video module that is commercially available. Since this size is small enough for surveillance application, the development of analog image sensor has slowed down. On the contrary, the size of digital camera modules continues to decrease, with more and more companies, such as Sony, Hitachi, Fujitsu and Toshiba joining the competition. The smallest digital camera module currently available is the TCM8230MD developed by Toshiba, with a size of 6 x 6mm. A CMOS camera developed by Fujitsu is shown in Figure 6-3, with a size of 7.8 x 6.98 x 3.95mm. Therefore, analog camera modules have reached its minimum size while that of digital camera modules will continue to decrease. Table 6-1 summarizes the comparison of miniaturized analog and digital cameras.

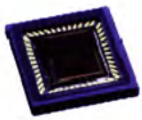

Figure 6-2 A CMOS/CCD image sensor

Figure 6-3 Left: A standard CMOS analog camera; Right: Fujitsu MB86S02A CMOS digital camera

Table 6-1 Comparison of Analog and Digital Video Cameras

Video Format	Analog (TV and VHS system)	Digital (VCD, DVD, HDTV)
Industrial Application	Surveillance Cameras	PDA, Cell phone, Digital Cameras
Size	Large (12x12mm)	Small (6x6mm)
Resolution	Medium	High
Power Consumption	High	Low
Circuit Interfacing	Simple	Complicated
Development	Slow	Fast

6.3 Digital and Analog Transmitters

Because of the rich information provided by video images, the bandwidth of an analog video is at least 6MHz, and the data rate of a digital video is at least 3.5Mbps for a 2fps system with CIF resolution. Therefore, the transmitter for video transmission has to be specially designed for this high volume of data.

A simplest analog video transmitter is a TV modulator which employs an amplitude modulation (AM) to up-convert the video signal to RF signal. The RF signal can then be picked up by a normal TV where the video can be displayed. As a result, no external or special circuit is needed at the receiving end. An example of the simplest

TV modulator which provides pin-to-pin connection is the MC44BS373C developed by Motorola, with size of 6 x 6mm. The modulator can also be constructed using surface-mount device (SMD) type transistor, resistors and inductors, which can give an even smaller circuit. The commercially available MC44BS373C transmits the RF signal in frequency range of VHF (30-450MHz) and UHF (450-880MHz), while a custom made transmitter can be made to transmit almost any frequency at or above the VHF range.

There are a lot of miniature digital transmitters developed specifically for the ISM bands of 434MHz, 915MHz and 2.4GHz, or for any other wireless applications. Transmitters designed for the 434MHz and 915MHz bands have slower data rate as they are mainly designed for carrying voice, text and command information. For example, the TRF4903 ISM Band RF Transmitter made by Texas Instrument has a maximum data rate of 64kbps, and hence cannot carry digital video data of at least 3.5Mbps. Chipcon's CC1100 multi-channel RF transceiver has highest data rate of 500kbps which is still too low, although it may be used for compressed video transmission.

Transmitter of 2.4GHz has a different story. There are 2.4GHz transmitters designed for ISM and general use, such as the Chipcon's CC2400 2.4GHz ISM Band Transceiver and the Nordic Semiconductor's nRF2401, which have programmable data rate of up to

1Mbps. Other than this, there are some other widely use technologies such as Bluetooth and WLAN. Bluetooth is designed for short distance (less than 10m) transmission and has a maximum data rate of 721kbps, while WLAN is designed for medium distance (within a building) transmission and has a maximum data rate of 22MHz. Among the different specifications of WLAN, both the 802.11b and 802.11g standards developed by the Institute of Electrical and Electronics Engineers (IEEE) are most widely used. There are a lot of chipset solutions developed by companies such as Intersil and Texas Instruments. 802.11b has a highest data rate of 11MHz and 802.11g has 22MHz. As a result, in terms of data rate, the WLAN technology is most suitable for video transmission. However, the WLAN solution is very complex and bulky. Even the smallest chipset solution PRISM 3® developed by Intersil has 2 chips, one of which is an RF IC and the other is a baseband processing chip.

For the 5GHz band, not a lot of solutions have been developed, mainly because this band is more susceptible to radio signal degradation. The IEEE 802.11a standard uses 5GHz as the wireless frequency and has a data rate of up to 54Mbps. Although it is not as widely used as 802.11b/g, 802.11a is seen as a long-term commercial successor to 802.11b/g as the 5GHz band not only allows faster data rates, but is also less densely populated with interfering equipment than the 2.4GHz band. Table 6-2 compares the digital transmitters using different technologies and Table 6-3 summarizes the comparison of analog and digital transmitters.

Table 6-2 Comparison of digital transmitters using different technologies

Digital Wireless Transmission Technology	**ISB Band Transmitter (434MHz, 915MHz)**	**ISB Band Transmitter (2.4GHz)**	**Bluetooth (2.4GHz)**	**WLAN 802.11b (2.4GHz)**	**WLAN 802.11g (2.4GHz)**	**WLAN 802.11a (5GHz)**
Range of Transmission	Short	Short	Short	Medium	Medium	Medium
Highest Data Rate	500kbps	1Mbps	721kbps	11Mbps	22Mbps	54Mbps
Circuit Complexity	Simple	Simple	Medium	Complicated	Complicated	Very Complicated
Video Transmission	Compressed Video	Compressed Video	Compressed Video	Uncompressed Video	Uncompressed Video	Uncompressed Video
Size	Small	Small	Medium	Large	Large	Large

Table 6-3 Comparison of analog and digital transmitter

Video Transmission	Analog	Digital
Property of Video Transmission	Large bandwidth (6MHz)	High data rate (3Mbps of CIF @ 2fps)
RF Frequency for Uncompressed Video Transmission	> 30MHz	> 2.4GHz
Circuit Complexity	Very Simple	Complicated
Size	Small	Medium

Chapter 7 Possible Solutions

7.1 Analog Camera + Analog Video Transmission

This is the simplest and most straightforward solution for the system. The analog video captured by an analog CMOS image sensor is sent to a TV modulator or an AM circuit to generate the RF signal in the range of 30-800MHz. The RF signal is then radiated through an antenna. A block diagram of the system is shown in Figure 7-1. This system is easy to build and visualize, and requires the least number of components. Although the size of commercially available analog cameras (20 x 20mm) is way larger than the acceptable size of a wireless capsule endoscope (11mm in diameter and 25mm in length), it is possible to custom made cameras to the required size.

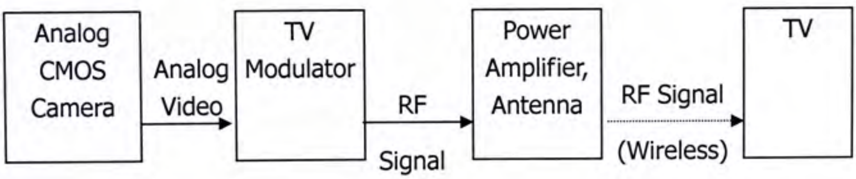

Figure 7-1 Solution of Analog camera + Analog video transmission

7.2 Digital Camera + Analog Video Transmission

This solution makes use of a digital camera instead of an analog one. Commercial digital camera has smaller size and can be easily obtained from the market. Because analog video transmission is easy and straight-forward, it is also used in this solution.

However, a converter is needed to convert the digital video signal outputted from the digital camera, to analog video signal to be inputted to the TV modulator. As a result, a video digital to analog converter (DAC) is needed. There are many video DACs available in the market for different application such as HDTV and DVD conversion. Only a few of them meet the digital video interface that are specified by individual digital cameras. The smallest one in the market is ADV7179 Video DAC (6x6mm) made by Analog Devices. It accepts 8-bit 27MHz YCrCb digital data and outputs PAL/NTSC analog video signal. After the conversion, the analog signal can be fed to the video transmission module in the same way as the previous solution. Figure 7-2 shows a block diagram of this solution. This solution is a bit complicated to implement and it has about the same size of the previous one, since the Video DAC IC has a small size of 6x6mm. Besides, the increase in solution size due to the addition IC can be compensated by the smaller size of digital camera.

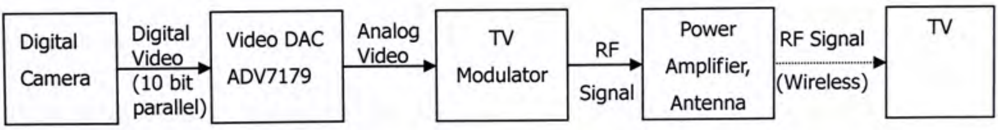

Figure 7-2 Solution of Digital camera + Analog video transmission

7.3 Digital Camera + Digital Video Transmission using WLAN Technology

This solution makes use of the WLAN technology, so that any computer connected to the WLAN network can pick up the video and display it in the computer. Since WLAN has data rate up to 22Mbps, high quality video can be transmitted without compression. However, the transmission circuit is very complicated. Firstly, digital camera outputs digital data in parallel. Image processor or data serializer is needed to serialize the parallel data before transmission. Then the serialized data has to be packaged according to the data communication protocol. As a result, a very fast and powerful Central Processing Unit (CPU) is required to process the high volume of data. The data can then be sent to the 802.11b/g chipset solution which processes the data so that it is ready to be transmitted by the antenna in 2.4GHz. At the receiving end, a computer with the standard WLAN hardware receives the RF data. However, in order to display the video in the computer, a program has to be written to process or extract the video information from the received data and reconstruct the images or the video. The system is illustrated in Figure 7-4.

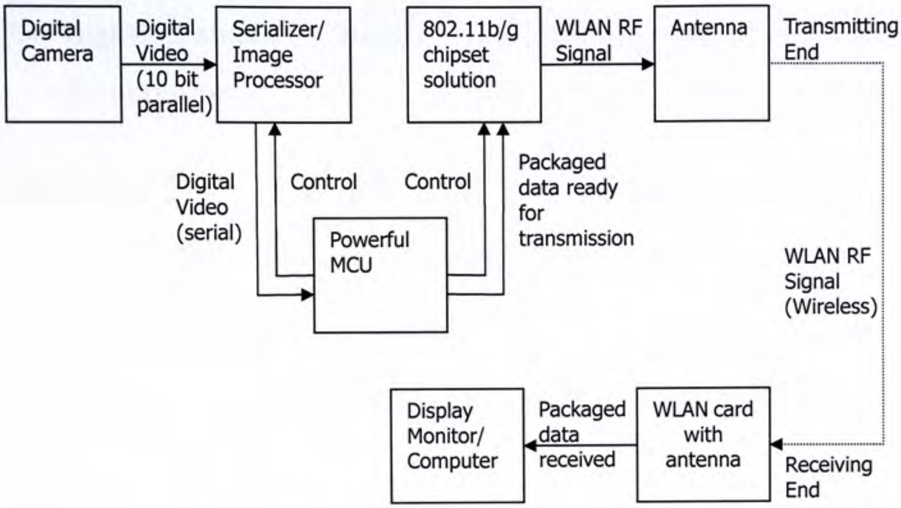

Figure 7-3 Solution of Digital Camera + Digital Video Transmission using WLAN Technology

As shown in the figure, this solution is very complicated and requires a lot of work. A program has to be written for the CPU to perform the required process, and another program has to be written at the receiving end in order to process and display the received video data. In addition, more circuit components have to be used, such as the Serializer and an extra CPU. Besides, current 802.11b/g chipset solution has a very bulky size which is impossible to fit in to a capsule. Therefore, this solution is not a possible choice, given the current technology.

7.4 Digital Camera + Digital Video Transmission with Video Compression

Figure 7-5 shows the block diagram of the solution. With video compression, the video data to be transmitted can be largely reduced. This allows the use of transceivers of lower data rate as well as narrower bandwidth. As a result, by using an Image Compression chip such as the JPEG (Joint Photographic Expert Group) Encoder OV528 made by OmniVision, the digital images captured by the camera are compressed into JPEG format. The OV528 Compression Engine converts 15fps images of 640x480 resolutions into serial JPEG data of 115.2kbps, which can be transmitted by most of the RF transmitters in the ISM bands of 434MHz, 915MHz and 2.4GHz. At the receiving end, similar hardware is needed to receive the signal and extract the JPEG data so that the images can be reconstructed and displayed in the computer.

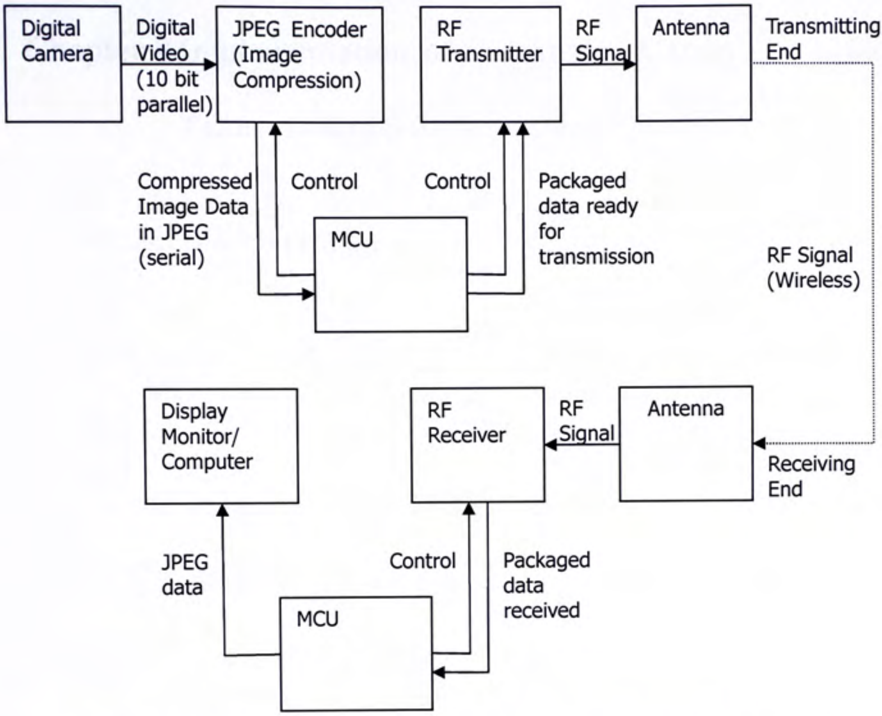

Figure 7-4 Solution of Digital Camera + Digital Video Transmission with Video Compression

Chapter 8 Implementation of the Analog Camera + Analog Transmission Solution

8.1 Circuit Implementation

In this prototype, a 1/4" CMOS analog camera VC-KTK702C made by Vtec Electronic Co was used. It had 628(H) x 582(V) of resolution with a size of 17.4 x 17.4 x 20.4 mm. For the RF modulator, a Motorola TV modulator chip, MC44BC373 was used. It could be programmed to radiate frequencies in the range of 30-880MHz, and its output power was -34.5dBm, which was enough for the demonstration. After considering different types of simple antennas, a helical antenna was chosen for RF transmission due to its compact size. The resulting antenna had 8mm in diameter and 5 turns. It was tuned to radiate at 800 MHz of frequency.

The lighting system was composed of four Kingbright KPHK-1608PWC white LEDs with size of 1.6mm x 0.8mm, and a 555 Timer circuit, so that the LEDs were given with pulses of current instead of a steady current, as this would save the most power. There were 3 parameters to be considered in this circuit: (1) the pulsing frequency (f_p), (2) the duty cycle of pulses (D), and (3) the forward current (I_F) of LEDs. In order to investigate how these three parameters affect the brightness and quality of the video, experiments were carried out. In the experiments, four LEDs were mounted on the camera as shown in Figure 8-1. The camera was then connected to a portable TV by a video cable so that the video captured by the camera could be viewed on the TV monitor. The camera was placed in a dark environment and it was set to capture images of a book cover.

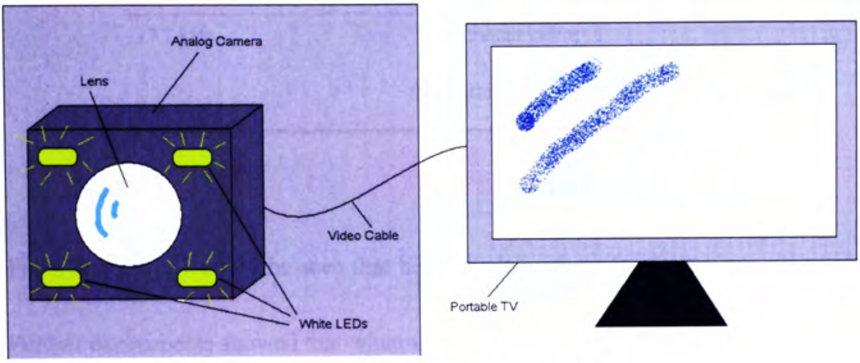

Figure 8-1 Experimental Setup of LED Experiments

The first experiment determined the effect of pulsing frequency. By fixing the other two parameters with an arbitrary value: D = 50% and I_F = 13mA, the effect of varying f_p was observed and recorded in Table 8-1.

Table 8-1 Experiment result of varying LED's pulsing frequency

Pulse frequency (f)	**Observation**
137 Hz	Horizontal stripes; Observable flashes
1.37 kHz	Observable strips; Very little flashing
13.7 kHz	Very smooth video; No flashing

From the result, it could be seen that higher pulsing frequency gave smoother video. Further experiments showed that when f_p was above 3 kHz, the video was smooth and no flashing was observed.

The second experiment concerned the duty cycle of pulses (D), which was defined as the percentage of ON time in a period, as shown in Figure 8-2. By fixing the other two parameters to arbitrary values: f_p in the kHz range, above 3 kHz for smooth video, and I_F = 13mA, the effect on video was observed and recorded in Table 8-2.

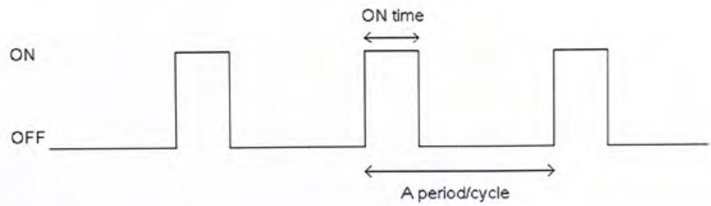

Figure 8-2 Duty cycle (D) calculation

Table 8-2 Experimental result of varying LED's duty cycle

Duty Cycle (D)	Frequency f_p	Observation
35%	5.4 kHz	Dim and stable
48%	7.3 kHz	Bright and stable
54%	8.1 kHz	Brighter and stable

Result showed that the higher the duty cycle, the brighter the LEDs and hence the brighter the video.

For the effect of LED's forward current (I_F) on the brightness of the LEDs, Figure 8-3 obtained from the datasheet of the LED showed that LED's luminous intensity, hence brightness was linearly proportional to the applied I_F.

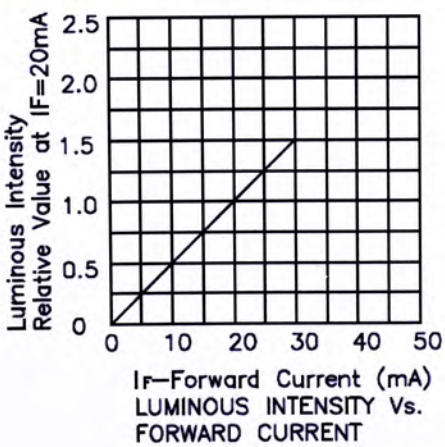

Figure 8-3 Relationship of Forward Current and LED brightness

From the above experiments, it was concluded that pulse frequency had to be above 3 kHz for stable video, and both duty cycle (D) and forward current (I_F) affected brightness of the LEDs. Therefore, the optimal design was to choose the highest possible I_F while lowering D to get an acceptable brightness, as this will save the most power by reducing the resistor R as shown in Figure 8-4 as much as possible.

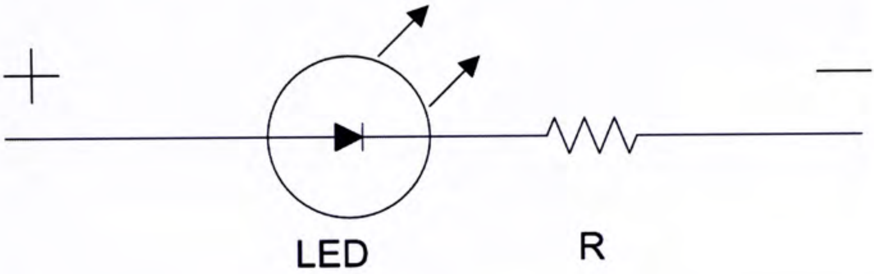

Figure 8-4 LED in series with resistor R

Finally, 50mA of LED forward current was used and the duty cycle of pulses was limited to 10% to give an acceptable brightness. The completed system is shown in Figure 8-5.

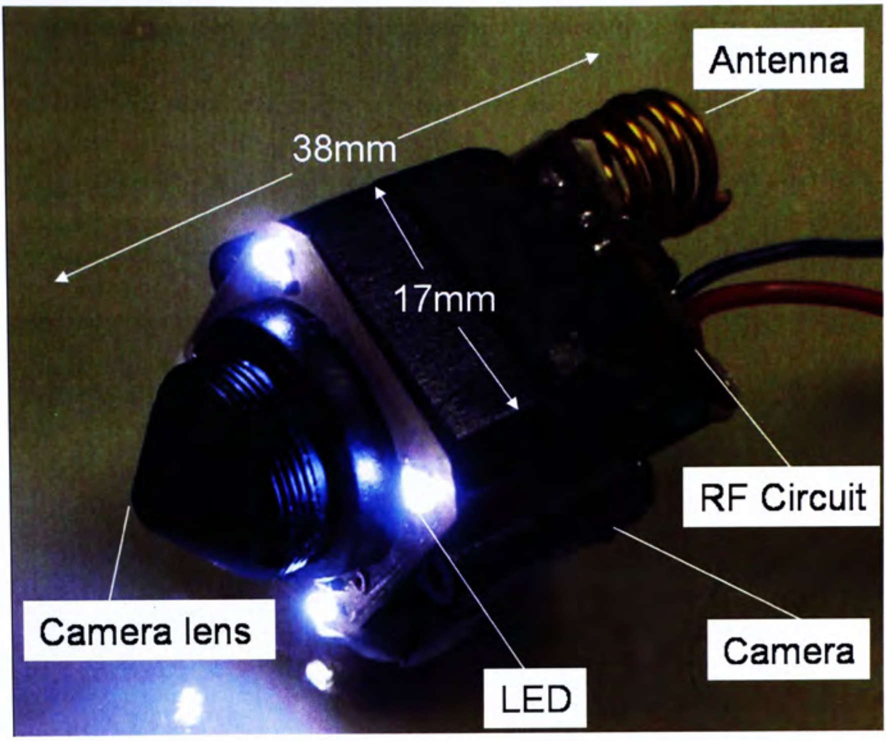

Figure 8-5 A picture of the complete system

8.2 System Verification

The system was put inside a plastic case with a transparent dome as shown in Figure 8-6 so that it could be used as a standalone device. The device was then pushed through a cleaned porcine colon. A portable TV with a straight antenna of 45cm was placed beside the colon at a 5cm distance to pick up the RF signal transmitted out of the colon. A few snapshots of the video captured by the prototype are provided in Figure 8-7. In the video, a few parameters were observed qualitatively: the smoothness, clearness and brightness of the video, as well as the amount of details that the video was able to show. As seen in the snapshots, images are quite clear and they show details of the colon lining. Although the images have a little noise due to the wireless transmission, it can be filtered at the receiving end by circuit technique or image processing technique.

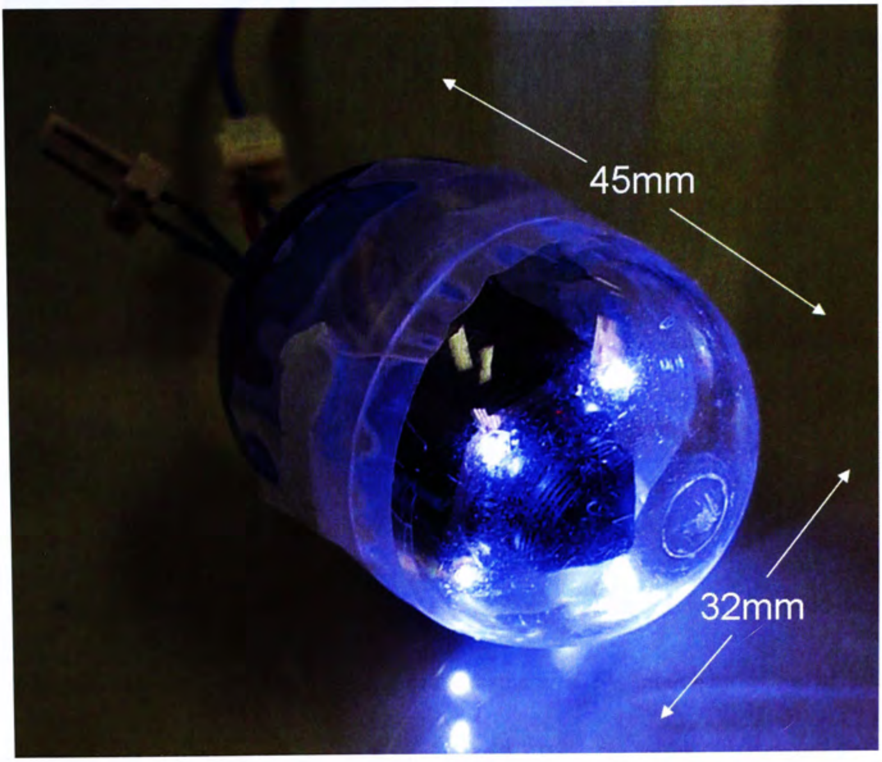

Figure 8-6 The standalone system - prototype wrapped inside a plastic case

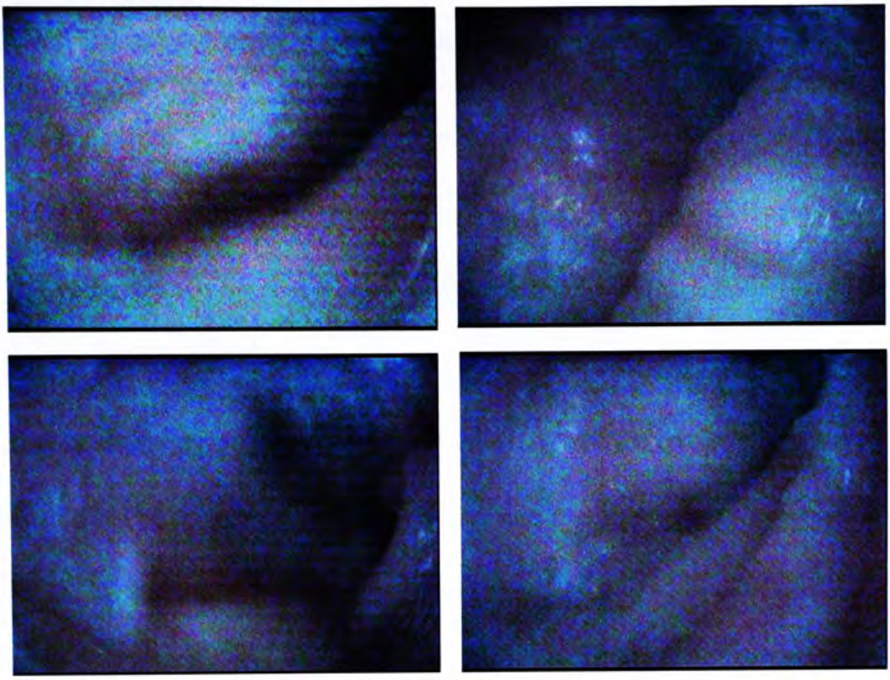

Figure 8-7 Snapshots of video taken by the prototype

8.3 Conclusions

In this chapter, a prototype of wireless capsule endoscope was designed and implemented using a CMOS analog video camera, a TV modulator IC, a helical antenna, and a lighting system with four white LEDs. The system made use of the current analog technology, including analog video and transmission. The prototype was verified in a clean porcine colon, to simulate a human intestine. By pushing the prototype inside the colon, the video camera captures video images and transmitted out of the colon through its helical antenna. A traditional TV with a straight antenna was placed beside the colon to receive the signal transmitted from inside the colon.

The implemented system is the most straight-forward solution, which involves the least number of circuit elements. However, the size of the prototype (32x45mm) is way larger than the size constraint (11x25mm) mentioned earlier. This is mainly due to the bulky size of the analog video camera (17x17mm). In the real implementation, a custom camera should be made to decrease its size to fit the constraint, and the RF module can be constructed using a few surface mount technology (SMT) components for smaller size and less power consumption.

Chapter 9 Conclusions and Future Work

9.1 General Conclusions

In this thesis, an experimental study was performed to investigate the effect of human body attenuation for radio waves at different frequencies (100MHz to 6GHz). It was found that the higher the frequency, the more the energy was absorbed by the body trunk model. In addition, at the 434MHz, 915MHz and 2.45GHz ISM bands, attenuation was found to be 10.78dB, 16.49dB and 37.5dB respectively. Although attenuation at 2.45GHz was quite high, the band can still be used for the wireless link given that the transmitter and receiver are well designed for higher sensitivity. As a result, all these three ISM bands can be used for Wireless Capsule Endoscopy and the prototype was built based on this experiment.

Different technologies for the wireless video transmission were discussed in Chapter 7. Analog modules are generally bulky but easy to implement, while digital modules are small in size but complex. Chapter 7 presented four solutions for wireless video transmission. Solution 7.1 uses analog cameras while the remaining use digital cameras. For wireless transmission, both solutions 7.1 and 7.2 use analog transmission while solutions 7.3 and 7.4 use digital. Implementation of solution 7.1 and 7.2 are easier because of analog video transmission but their sizes will be too bulky for Wireless Capsule Endoscopy, unless custom made components are used. Solution 7.3 which makes use of the WLAN technology has the advantage of very fast data rate, but its size is large too because of the circuit complication. Solution 7.4 makes use of image compression and the circuit can be made a little bit simpler as a smaller transmitter can be used.

Out of the four proposed solutions, only solution 7.1 was implemented because of time limitation. This solution was the simplest one and could demonstrate the concept of Wireless Capsule Endoscopy. A 1/4" CMOS analog camera analog camera and a TV modulator chip, Motorola MC44BC373 was used as the video transmitter. It was programmed to transmit at frequency of 800MHz. A coil antenna was tuned to radiate at this frequency and a lighting system consisting of four LEDs were built. The resulting circuit was packaged in a circular plastic case with a transparent dome and pushed inside a porcine colon in vitro. A straight TV antenna was placed at a distance of 5cm from the colon to pick up the video transmitted from the device, and the video was displayed on a traditional TV. The function of the prototype was verified by viewing the motion pictures that the prototype captured inside the porcine colon on the TV.

9.2 Future Work

In this thesis, only one solution out of the suggested four was implemented. Therefore more work can be put in implementing the remaining three solutions and analyze the challenges involved. In addition, the implemented prototype has a size of 32mm (diameter) x 45mm (length) which is larger than the proposed Wireless Capsule Endoscope of 11mm (diameter) x 25mm (length). As a result, more work should be put in minimizing the prototype into the desired size. Although commercial analog CMOS cameras are huge in size, the technology for making miniaturized analog cameras exists because digital cameras are actually made from analog cameras. Therefore custom made analog CMOS cameras should be investigated and implemented in the solution.

Power supply and consumption has not been considered when designing the prototype, and therefore more research has to be done to investigate the possibility of minimizing power consumption of the device, as well as increasing the power capacity of the batteries.

Another suggestion for miniaturization of Wireless Capsule Endoscope is to design an ASCII solution for the system, similar the one suggested by X. Xie et al[24]. The ASCII solution will contain an image processing module, a control unit and the transmitting module. By developing an ASCII solution, the size of the device can be largely reduced, and rooms can be used for other functions such as locomotion and actuation.

With the advancement of video encoding technology and the miniaturization of large storage device, a possible solution of Wireless Capsule Endoscope is to include a storage device in the endoscope to store the video data. Video encoding technology allows the video to be stored using the least amount of memory, while the miniaturization of storage device enables the device to be installed in the capsule. This not only simplifies the system as receivers and recorders are no longer needed, it also decreases the potential risk that the patient has to bare as there will be no radiation energy emitting from the capsule. Therefore, more investigation can be done in this direction for future work.

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LIST OF ABBREVIATIONS

AM	Amplitude Modulation
ASIC	Application Specific Integrated Circuit
CCD	Charge-Coupled Device
CIF	Resolution of 352x228
CMOS	Complementary Metal Oxide Semiconductor
CPU	Central Processing Unit
CT	Computed Tomography
DAC	Digital to Analog Converter
dB	Decibel
DVD	Digital Versatile Disc
FCC	Federal Communications Commission
FDTD	Finite Difference Time Domain
FM	Frequency Modulation
Fps	Frames Per Second

GI	Gastrointestinal
HDTV	High Definition TV
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
JPEC	Joint Photographic Expert Group
LEDs	Light Emitting Diodes
MRI	Magnetic Resonance Imaging
NaCl	Sodium Chloride
OFTA	Office of the Telecommunications Authority
PMMA	Polymethyl Methacrylate
RF	Radio Frequency
SAR	Specific Absorption Rate
SMA	Shape Memory Alloy
SMD	Surface Mount Device

SMT	Surface Mount Technology
TV	Television
UHF	Ultra High Frequency
VCD	Video Compact Disc
VHF	Very High Frequency
VHS	Video Home System
WLAN	Wireless Local Area Network

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