Energy efficient medium access control protocol for in-vivo multiple capsule networks

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Energy Efficient Medium Access Control Protocol for In-Vivo Multiple Capsule Networks

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Abstract

Wireless capsule endoscopy is a type of medical device for diagnosing diseases inside small intestine giving little discomfort to the patients. It is envisaged that several capsule devices with different functionalities work together to perform some monitoring/therapeutic work. The capsules and the outside coordinator form a wireless network. As the capsule devices are powered by batteries that are difficult to replace, energy efficient MAC protocol plays an important role. This thesis focuses on proposing a novel energy efficient Medium Access Control (MAC) protocol for multiple capsule networks.

The thesis reviews the engineering aspects of wireless capsule endoscopy and the current technologies, including in-vivo wireless communication, wireless power supply, active locomotion and localization. Later, a comprehensive survey of MAC protocols for wireless sensor networks and body sensor networks is conducted.

Multi-hop communication through the human body is simulated for different circuitry power. The result shows that it can save energy compared with single hop wireless communication when the circuitry power is lowered to 100 μ W. This was already achieved in the lab. Based on this result, a novel TDMA based MAC protocol is proposed for multiple capsule networks. It follows an uplink, downlink asymmetric topology giving lower power consumption. The TDMA frame is proposed in detail.

Changeable frame format and adaptive power control further reduce the energy consumption. Simulation result shows that the proposed MAC protocol consumes less energy than 802.15.6 draft when circuitry power is 100 μ W based on randomly generated mobility pattern. Hardware implementation of the proposed TDMA MAC protocol has been conducted.

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Chapter 1 Introduction

1.1 Background

The advancement of electronics, wireless communication, and MEMS technology vastly promote the progress of health monitoring and medical examination. Many new products are introduced, such as wrist pressure monitors, wrist heart rate monitors, body implants, blood glucose sensing, cardiac pacemakers, etc (Table 1.1). Wireless capsule endoscopy (WCE) is one of such electronic medical examination devices which is gaining strong acceptance by patients suffering from gastrointestinal disorders [1]. Patients with gastrointestinal disease swallow the capsule endoscopy and the capsule would move inside gastrointestinal (GI) tract by peristalsis. It takes pictures by its camera inside, then send the data wirelessly to the outside receiver for doctor viewing (Fig. 1.1)(Fig. 1.2).

Table 1.1 Sensing Activities in BSNs [2]

Wearable devices	Implantable devices
EEG	Glucose sensor; Cardiac arrhythmia
ECG	Pacemaker; Cardioverter;
SpO2 pulse oximeter	Defibrillator
Glucose	Intracranial pressure sensing
Fall detection	Wireless capsule drug delivery
Emergency call	Deep brain stimulation
Performance	Retinal sensors; Parkinson's;
assessment	Epilepsy
	Insulin pump

Fig. 1.1 Wireless capsule endoscopy [3, 4]

Compared with the traditional push endoscopy, the wireless capsule endoscopy gives patients little discomfort, and can examine some parts of small intestine which is out of the reach of traditional push endoscopy. The mutually contradicting conditions limits the pushing distance of traditional push endoscopy: it should be flexible enough to follow curvature and folds of the intestine, while on the other hand, it should also be rigid enough to be pushed into the intestine.

Fig. 1.2 Images taken by PillCam [5]

Besides the capsule itself, the whole system includes data recorder, antenna, and work station (Fig. 1.3). Data recorder is a device that receives the data from wireless

capsule and stores them. There are eight antennas attached around the human body and they are connected to the data recorder. Work station is usually a PC for processing data. After examination, the doctor connects the data recorder to work station to download the image data. At the work station, data can be viewed by doctors.

Fig. 1.3 The whole system of capsule endoscopy[6]

Several companies have been focusing on the wireless capsule endoscopy such as Given Imaging[7], Olympus[8], OMOM[9], and IntroMedic[10], and have released their capsule products (Fig. 1.4). There is a huge commercial and research value on this kind of small wireless capsule. The research works are mainly about improving the quality like increasing operating life, improving the image resolution, and adding new functionalities into the wireless capsule endoscopy. Making the capsule smaller

and more power efficient are the two major concerns during the design.

Fig. 1.4 Related companies about wireless capsule all over the world

1.2 Motivation

Although wireless capsule endoscopy gives a comfortable examination of the patients, the need for more powerful and functional wireless devices inside the human body performing more advanced operations is expected. The future wireless capsule will be a capsule robot or several robots which co-work for a common task. Because of the miniature size and the in-vivo operating conditions, there are huge challenges in designing the powerful capsule robots, especially in the power consumption aspect. Reduce power consumption becomes a very important issue.

Multiple capsule robots will be a very interesting, useful, and challenging topic. It is envisaged that a patient ingests more than one capsule over a short period of time, and these capsules will cooperate, in-vivo, to complete a single coordinated task. The use of a multiple capsule system can realize many applications which cannot be performed in a one capsule system. Examples of such applications include long term and short term monitoring of GI tract, segmental image capturing, surgery cooperation, etc.. The capsules and the wireless data recorder, which is attached to abdomen, form a wireless network. It is a subset of body sensor networks (BSNs).

The current capsule devices are powered by two 1.5V, 80mAh button batteries. It can last 8 hours to perform only the basic function of capturing and transmitting images with a frame rate of 2 frames/second [11]. Efficient utilization of the limited energy is an issue. It is a well known fact that the radio transceiver consumes a large part of the energy budget of wireless sensor devices [12] and a good medium access control (MAC) protocol can efficiently reduce the energy consumed by the transceiver. Many energy efficient MAC protocols have been proposed for wireless sensor networks (WSNs) and BSNs [13-17]. However, multiple capsule networks have some unique properties such as mobility, the size of the operating area, scalability, safety, reliability, etc., so specific energy efficient MAC protocols for multiple capsule networks are necessary. This thesis focuses on MAC protocol design for multiple capsule networks regarding saving power.

1.3 Objectives and Scope

This research focuses on new technologies of wireless capsule endoscopy and the multi-capsule scenario. The general objective is to design and optimize a MAC protocol of the multiple capsule networks mainly to address power consumption issue. Detailed objectives are listed as follow.

1. The first objective is to investigate all the new technologies of wireless capsule endoscopy and find the research direction. This thesis finally focuses on multiple capsule networks.
2. Conduct a complete literature review on the MAC protocols of WSNs and BSNs.
3. Simulate and discuss the feasibility of the multi-hop communication for in-vivo multiple capsule networks.
4. Propose a solution of MAC protocol in detail for multiple capsule networks.
5. By simulation and experiment, validate the topology design and communication protocols indeed giving a lower power for the multiple capsule networks.

1.4 Organization of Thesis

The thesis contains six chapters in total. They are organized in the following manner:

Chapter 1 introduces the background and motivation of the multi-capsule networks.

The objectives and scope are also outlined along with the organization of the thesis.

Chapter 2 gives a literature review of wireless capsule endoscopy. It will consist of the several techniques about wireless capsule endoscopy: wireless communication, wireless power supply, active locomotion and localization.

Chapter 3 gives a literature survey on WSNs and BSNs regarding medium access control protocols.

Chapter 4 describes the details of MAC protocol design for multiple capsule networks. Multi-hop communications through the human body is discussed and the simulation results show a better performance than single hop communication in terms of power consumption when circuitry power is low enough. An uplink, downlink asymmetric topology is introduced. The MAC protocol based on TDMA is proposed giving lower power consumption. The TDMA frame is given in detail. Changeable frame format and adaptive power control further reduce the energy consumption.

Chapter 5 describes the hardware implementation of the proposed protocol. IEEE 802.15.6(draft) and proposed TDMA protocol are tested using CC1110 from TI.

Chapter 6 gives the conclusion. When the circuitry power is reduced to certain level in the near future, the proposed TDMA MAC protocol is energy efficient for the multiple capsule networks. The future works are described.

Chapter 2 Survey of Wireless Capsule Endoscopy

This chapter aims to survey the development of the technologies used in the wireless capsule endoscopy. It reviews the state-of-the-art technologies and describes the difficulties faced when developing such cutting edge devices. The reviewed areas include system constitution, in-vivo wireless communication, wireless power supply, motion mechanism and localization for capsule systems.

2.1 Wireless Capsule Endoscopy and The Whole Diagnosis System

Fig. 2.1 shows the structure of the wireless capsule, M2A from Given Imaging Ltd. The capsule measures 11mm×26mm (diameter×length) and weighs 3.7g. It contains a CMOS (complementary metal oxide semiconductor) video camera, white light LED (Light emitting diodes) illumination sources, two silver-oxide button batteries, and radio telemetry transmitter [18-20]. The whole diagnostic system comprises a capsule endoscopy, a data recorder, and a work station. Data recorder is a hard drive with 8 skin antennas which can be attached to the human body and receive the data transmitted from the wireless capsule [21]. Once swallowed, the capsule moves by peristalsis. The images are captured at 2 frames per second and are transmitted by radio frequency to antennas on the body surface. After 8 hours examination, the antenna array and data recorder are removed and the recorded digital information is downloaded into the work station (usually a PC), then the doctor can view the images

of the small intestine. The capsule is expelled naturally, usually within 24 to 48 hours [22]. Patients should return the recorder, antennas, and belt, but do not need to return the disposable capsules. The block diagram is shown in Fig. 2.2.

Fig. 2.1 Structure of the capsule: 1. optical dome, 2. lens holder, 3. short focal length lens, 4. LEDs, 5. CMOS image sensor, 6. two batteries, 7. ASIC RF transmitter, 8. antenna [20]

Fig. 2.2 Block diagram of Given Imaging diagnostic system [1]

The history of wireless capsule can be dated back to 1950's and 1960's. At that time, the capsule can monitor temperature [23], pressure [23, 24], PH value [24, 25] in the

GI tract. In 2000, during the Digestive Disease Week Conference in San Diego, California (USA), P. Swain, an endoscopist from the London Royal Hospital, and Given Imaging Ltd., announced the M2ATM pill, the first swallowable capsule able to capture images inside the small bowel [5]. From then on, both medical doctors and engineering researchers, paid more and more attentions on the clinical trials and improvement of the performance of WCE.

In medical aspect, doctors focus on justifying the performance of capsule endoscopy [26, 27] and optimal diagnosis procedure. Although Given Imaging recommends fasting for 10 hours without bowel purge before swallowing the capsule [7], there are some evidences that using polyethylene glycol [28], sodium picosulfate [29], sodium phosphate [30], or simethicone [31] may give better imaging [18]. However, some have raised the concern that in patients who are having WCE for obscure gastrointestinal bleeding (OGIB), preparation fluids may wash away any blood important for localizing a culprit lesion [32]. Several indications for wireless capsule endoscopy are investigated, including OGIB [18], Crohn disease [21], polyposis syndromes, small bowel tumors, celiac disease, and abdominal pain. The clinical trials show that WCE gives a higher sensitivity for detecting and a unique ability to examine the whole small bowel. At the same time it gives little discomfort compared with other enteroscopes. However, there also exist some disadvantages of WCE. The examination duration is only around 8 hours, but the whole time through the GI tract is 24-48 hours [22]. The power supplied is far from enough. In some situations like

strictures or motor dysfunction, the capsule endoscopy is restricted used since it has a risk of capsule impaction [21]. The capsule endoscopy may get stuck in the small bowel.

In engineering aspect, the wireless capsule of the future world will be much more powerful. To some extent, it will envisage a multi functional robot. It is expected that it will not only capture images in the GI tract, but also deliver drugs, sample tissues, perform simple surgeries, and so on. All of these are controlled by the operators in a real time mode. The resolution of image will be improved and the examination duration will also be extended by both increasing supplied energy and reducing power consumption of the current capsule. The sensitivity and specificity of automatic detection of no bleeding lesions would be increased. This chapter focuses on the engineering aspect of WCE. The details of key techniques are discussed and the comparison and implementing difficulties are elaborated (Fig. 2.3).

Fig. 2.3 Diagram of techniques of capsule endoscopy

2.2 Wireless Communication via Human Body

Wireless communication is the prerequisite for proposing wireless capsule endoscopy. As the new wireless communication technology develops, using wireless signal transmission to convey the image data to the outside human body becomes possible. The sensor data is sent by the capsule transceiver at certain frequency to the base station and the command is sent by the base station to the capsule endoscopy wirelessly. Wideband, energy efficient communication is expected by optimizing the modulation scheme, the antenna design and wireless network protocols of ingestible wireless capsules.

For in vivo communication through the human body, the first thing considered is whether it is harmless to human body. Electromagnetic influences on biological tissue causes thermal effects. For safety of human exposure to radiofrequency fields, Federal Communications Commission (FCC) [33], International of Electrical and Electronics Engineers (IEEE) [34], International Telecommunication Union (ITU) [35] and International Commission on Non-Ionizing Radiation Protection (ICNIRP) [36], provide guidance and recommendation on protection from non-ionizing radiation (NIR). Specific Absorption Rate (SAR) (unit: W/kg) is widely accepted metric for the thermal effects [37]. For MICS, the power is set to a maximum of 25 uW ERP according to European Telecommunications Standards Institute (ETSI) and 25 uW EIRP according to FCC & ITU-R [22]. Here, the 25 uW limit applies to the signal level outside of the human body. For implant devices, the power level is allowed to be

increased to compensate for body losses. The design of wireless communication system, as well as wireless power supply mentioned in section 2.3, must satisfy the requirements for safety.

For the modulation scheme, Yuan et al. [38] and Kihyun et al. [39] implemented their transceivers using on off key (OOK) modulation. In OOK system, binary 1 is represented by a short pulse and binary 0 is represented by no pulse transmission. Unlike the conventional transmitter which requires a continuous running local oscillator, a fast turn-on VCO can be turned on only when a “1” signal need to be transmitted and remain power off during the rest of the period. Since the duration of the pulse only occupy a small portion of the signal period, the transmitter can achieve low power consumption using power gating technique. Jung-Yeol et al. proposed a novel phase silence shift keying (PSSK) modulation scheme for high data rate implantable medical devices [40]. PSSK is a kind of PSK scheme. It is more bandwidth efficient than the orthogonal modulations such as PPM, FSK, and OOK. Based on PSK, PSSK combines the PPM technologies to use one bit to determine the absence that is the position of silence envelope of the symbol. Because the transmitter of PSSK transmits only half energy of the symbol for a symbol period, it can save the transmit power by 3dB.

Antenna is another research spot of the wireless capsule endoscopy. Sang Heun et al. proposed a fat arm spiral antenna for wideband ingestible capsule [41] as shown in

Fig. 2.4. The height of antenna is 4mm and the diameter is 10mm. The bandwidth is 460-535MHz with an omni-directional radiation pattern. Huang et al. proposed a small micro strip antenna at 915 MHz [42] (Fig. 2.5). There is an offset of 35MHz between the resonant frequencies in the human body model. Fig shows these two antennas. The dimension and the bandwidth performance prove that they are good choices for being used in the ingestible capsules.

Fig. 2.4 Fat arm spiral antenna [41]

Fig. 2.5 Microstrip antenna for wireless capsule endoscopy [42]

For in vivo wireless communication, body tissue absorbs RF radio, which makes the channel different from usual wireless communication. It is mainly due to the electrical

property of tissue namely conductivity and permittivity [43]. W. G. Scanlon's report about radio propagation characteristics of an implanted source shows that the net body pathloss reaches over 20dB, a very significant effect of body tissue on radio propagation [44].

Some researchers focus on the influence of tissue properties and frequency on RF attenuation characteristics, and they found that the depth to which microwaves can penetrate tissue is primarily a function of the dielectric properties of the tissues and of the frequency of the microwaves. In general, the lower the water content of the tissue, the deeper a wave at a given frequency can penetrate. Also, at the frequencies of interest, the lower the frequency, the larger the depth of penetration into tissues with given water content [45, 46].

Because the electronic component is absorbed greatly by low-reluctance biological tissue, while the magnetic fields are largely unaffected, near field data transmission using magnetic coupling to transmit and receive the signal is proposed by the researchers (Fig. 2.6) [47]. The relatively low frequency of tens of megahertz is adopted to minimize the signal attenuation. L. Wang's results show a good performance about the magnetic coupling [46]. The near field transmission has much more complicated model than the far field transmission. The conventional RF transmitter analysis is inappropriate for near field transmission. One of the challenging areas is the antenna design which must operate at low frequency. Since the near field

magnetic field falls in magnitude much rapidly, the modeling of the mobile capsule data transmission is not easy.

Fig. 2.6 Magnetic coupling and radio transmission[47]

Percutaneous signal transmission is another transmission scheme. The wall of GI tract is considered as the medium or “wire” to transmit signal. There are similar researches about using body surface as transmission medium [48-50], but the features of the GI tract wall and body surface have different electrical properties. Further research needs to be done. A specific challenge should be considered here: the capsule is not wrapped tightly by the wall of GI tract. On average, the diameter of the small intestine of an adult human measures approximately 2.5-3 cm depending to different person [51], while the diameter of WCE is 11mm, so normally it somehow “swims” inside the GI tract. It would cause two problems in the research. One is image capturing. Because of the swimming characteristic, the camera direction would change all the time, so the captured image may be too confusing to recognize. The other potential problem for percutaneous transmission is connection. Researchers need to ensure that the capsule can keep an effective connection with the wall when communicating.

2.3 Wireless Power Supply

Capsular endoscopy is rapidly gaining credits among gastroenterologists. However, its evolution from a passive screening tool towards a multipurpose robot is far from straightforward. A bottleneck affecting all the commercial capsules is the limited available battery power, providing typically 25mW for 6–8 h. This amount of power is barely sufficient to transmit even low resolution images at low data rates and it certainly is inadequate to feed actuators for, e.g. locomotion or other highly consuming modules. Table 2.1 shows the power consumption of the main modules of the robotic capsule [52].

Table 2.1 Power consumption of the main modules of the robotic capsule [52]

Device	Required power	Operating time
CMOS image sensor	40mW	70-100%
LED illumination	4×10/20 mW	70-100%
Control electronics	10mW	100%
Compression chip	7.5mW	70-100%
Auto focus system	12mW(@50V)	50-80%
Locomotion system	>300mW	3-5%
Transmitter	5mW	100%
Receiver	<5mW	1-80%

More energy is expected but the limited space restricts the number of batteries in the

wireless capsule endoscopy. The researchers try to save energy for every energy consuming part. The complementary metal oxide silicon (CMOS) image sensors, which have low power levels compared with charge coupled device (CCD) sensors, are used as image acquisition devices. The power management module is considered to be put into the control circuit to minimize the energy consumption. For wireless data transmission through the human body, the frequency selection is also analyzed. Choosing a relatively low frequency can reduce the transmission power, therefore reduce the whole energy consumption [45, 46]. Besides reducing energy consumption, the researchers also incline to transmit power wirelessly to the ingestible capsule. By this way the capsule does not need to carry batteries but owns infinite energy. Inductive coupling is a valid alternative to batteries since it significantly increases the available power without imposing constraints to the time of operation.

S. Y. Yang et al. designed a power transmission system which can offer the maximum current of 980mA and the maximum power of 7.2W [53]. Shiba et al. proposed a design method for high efficiency energy transmission transformer that can transmit energy transcutaneously to small implantable medical devices using electromagnetic induction [54]. It specifies the material parameters of the transformer and then optimizes the transmission efficiency in terms of the design parameters defined by the users. This method can be readily used to calculate the extract transmission efficiency for changes in the material and design parameters. A maximum efficiency of 33.1% can be obtained at a transmission frequency of 500KHz and 100mW receiving power

for coil size of $\text{Ø}5 \text{ mm} \times 20 \text{ mm}$.

Lenaerts et al. proposed a 3D orientation power link [55] as shown in Fig. 2.7. The freedom of motion of the wireless capsule imposes the use of multiple coils internally. The power receiver comprises three coils which are geometrically orthogonal to one other, ensuring adequate coupling with the primary coil for any orientation of the capsule. The coils were wound out of full copper wire with a diameter of $100 \mu\text{m}$. The assembled receiver is a cylinder with outer dimensions of $\text{Ø}10 \text{ mm} \times 13 \text{ mm}$. the power efficiency of the link is measured to be 1% under worst case geometrical conditions. Up to 150mW of usable DC power can be delivered for the entire duration of its travel along the gastric track. Carta et al. put the ferrite core into the power receiver and adopted Helmholtz coil at the primary side based on the Leraetz's works [52]. The volume is reduced by 5% to 0.48cm^3 and the received power increases by 120%.

Fig. 2.7 Wireless power supply system for WCE [55]

Xin et al. introduced the ferrite core into the power receiver [56]. The outer dimension of the power receiver is $\varnothing 10 \text{ mm} \times 12 \text{ mm}$. the transmission power is 25W and the resonant frequency is 400KHz. At least 310mW usable power can be transmitted under the worst geometrical conditions. The SAR and current density of human tissues are 0.329W/kg and 3.82 A/m^2 , respectively. This is safe according to the basic restriction of ICNIRP.

Wireless power supply is very promising and will be manufactured into the future ingestible capsule. However, there are still some works which need to be done. First, the power receiver is expected to be designed smaller and the transmitter device outside the human body is expected much easier to carry by patients. Second, at the current stage the orientation stability is not satisfactory compared with the position stability. Further study about the structure of the coil and the type of receiving circuits should be carried out. Third, the transmission efficiency needs to be improved. The resonance frequency cannot be increased arbitrarily so as to maintain a low radio absorption by the body tissue, therefore other effective methods to improve the transmission efficiency are expected.

2.4 Locomotion Mechanism for Wireless Capsule Endoscopy

The movement of the current WCE is by peristalsis, while in the future the movement may be controlled by the operator. The operator can control the capsule to move

forward, backward, or stay in a fixed position. The speed of the motion should be controlled too. Many researchers try to design a best mechanism to implement the motion. Louis Phee et al. designed a kind of “inchworm” locomotion device based on extensor and clumper mechanisms as Fig. 2.8 [57]. Yeon Kwan Moon et al. proposed an electrical stimulus capsule which integrates two electrodes on the both sides of the capsule. The electrodes stimulate the wall of GI tract and the intestine contracts, by which the capsule is driven to move (Fig. 2.9 and Fig. 2.10) [58]. M. Quirini et al. designed a more complicated but more powerful mechanism, pill-sized 4/8/12-legged endoscopic capsule robot (Fig. 2.11) [59, 60]. Magnetic actuation is another way to control the capsule. The most obvious advantage is that no extra power is needed. A permanent magnet is put into the capsule, and the operator controls the outside magnetic field to drive the capsule (Fig. 2.12). Several papers discussed the design of the system [61-63].

Fig. 2.8 “inchworm” locomotion device[57]

Fig. 2.9 Prototype of the fabricated wireless electrical stimulus capsule[58]

Fig. 2.10 Principle for changing the direction of capsule movement[58]

Fig. 2.11 (a) 4-leg endoscopic capsule robot (b) 8-leg endoscopic capsule robot (c) 12-leg endoscopic capsule robot [59, 60]

Fig. 2.12 Conceptual diagram of the capsule guidance principle [8]

2.5 Localizing Wireless Capsule Endoscopy

Localization system is for determining the position of the ingestible capsule inside GI tract. This performs an important function as the doctor needs to know where the data is collected for the correct diagnosis to be performed. For example, in the event that the camera detects a tumor in the GI tract, the location of the tumor has to be known in order for treatment to be effectively performed.

To determine the location of the capsule, a sensor array is attached to the body with an appropriate distance to each other. This sensor array receives the signal generated by the capsule to estimate the distance between the capsule and itself. The position of the capsule can then be calculated using triangulation techniques based on the different distances measured from the individual sensors. There are three techniques for estimating the distance between the capsule and the sensor: signal strength detection

[64], magnetic field strength detection [65] and time arrival delay detection. A comparison of these three techniques is given in Table 2.2.

Table 2.2 Comparison of different techniques

	Signal intensity	Magnetic strength	Time arrival delay
Influenced by attenuation of body	Yes	No	Yes
Special signal for localization	Yes	No	Yes
Strict time synchronization	No	No	Yes
Extra space in the capsule	No	Yes	No

2.6 Summary

This chapter introduces the characteristics and the system constitution of in-vivo wireless capsule endoscopy for GI tract examination. The engineering aspects, such as wireless communication, wireless power supply, locomotion, localization, of wireless capsule endoscopy are discussed. There are also some other related research aspects like advanced vision system, tissue sampling, drug delivery, etc.. It can be seen that there are many research activities in the future to improve the quality of the useful wireless capsule.

Chapter 3 Literature Review on MAC Protocols of Wireless Sensor Networks and Body Sensor Networks

This chapter gives a complete literature review on MAC protocols for WSNs and BSNs. IEEE 802.15.4 and IEEE 802.15.6 draft are given out. The constraints of WSNs and BSNs are analyzed and the latest proposed MAC protocols are discussed in detail.

3.1 Basis of Medium Access Control

With the development of wireless communications and electronics, low cost, low power, multi-functional sensor nodes in small size come out. These sensor nodes, which have the ability of sensing, data processing, and communicating, form a wireless sensor network to perform some common tasks. Wireless sensor networks have a wide range of potential applications in the areas of health, military, and home. For example, the characteristics of rapid deployment, self-organization, and fault tolerance of sensor networks make them a very good choice for military control and communications. In the health field, sensor nodes can be deployed on the human body to monitor patients and assist disabled patients.

Medium access control is a very important part for wireless sensor networks. This is because for wireless network, the nodes share the common medium, so severe radio

interference can be caused. Collision, overhearing, idle listening, and overhead all waste a lot of energy. The sensors always use batteries and these are not easily replaceable. Hence a good MAC layers protocol is very critical for reducing power consumption for this kind of power constraint communication network.

A MAC protocol provides several basic functions. First, it provides medium access control for sensor devices to participate in communication at certain time. Second, it defines frame format, adds the MAC layer header at the TX side and remove it at the RX side. Third, it provides reliable transmission scheme ACK and retransmission between sensor nodes.

Limited energy resources is a major concern for WSNs protocol design, therefore, many MAC protocols focus on reducing energy consumption. Sensor nodes conserve energy by switching off unused parts because most hardware consumes a non negligible amount of energy even when they are not active. The sensor node coordinates with its neighbor to make both of them remain in the active state and communicate. Limited memory and computational resources also complicate the implementation of the functionalities which are commonly available in traditional networks. Protocols must take clock drifts into consideration. They also need to adapt to the changes quickly when sensor nodes run out of their energy resources and die. Adaptive MAC protocols also have to deal with mobility of sensor nodes and the effect of grey areas more easily. Finally, WSNs have a wide range of applications

with different requirements and characteristics. Researchers have to develop the protocols that fit the particular application requirements.

Network topology determines the way that different devices on the network are arranged and how they communicate with each other physically and logically. There are three main topologies for wireless communication networks: star topology, mesh topology, and tree topology. For star topology (Fig. 3.1(a)), all devices are connected to a single central controller often referred to as coordinator or master. The peripheral nodes are called slaves. Slaves can only communicate with the master. Communication between slaves requires passing all data through the master. For mesh topology as shown in Fig. 3.1(b), any device can communicate with other devices as long as they are in range of one another, which is called peer-to-peer network. Multi-hop networking protocols enable routing of packets from one device to the other on the network. For tree topology in Fig. 3.1(c), Tree topology is a special case of a multi-hop mesh network where there is always only a single path between two devices. The first device starting the network becomes the root of the tree. Another device can join the network as “child” of the root node and in turn allow other devices to join the network through that device. Devices are aware of their “parent” node and any “child” nodes. This hierarchical topology reduces routing complexity. The advantages and disadvantages of the three kinds of topologies are shown in Table 3.1. These three topologies can also be combined to form the hybrid topology.

Fig. 3.1 Network topologies

Table 3.1 Advantage and disadvantage of different network topologies

Topology	Advantage	Disadvantage
Star topology	<ul style="list-style-type: none"> • Simplicity • Low power consumption of slave nodes • Low latency and high bandwidth • Centralised systems 	<ul style="list-style-type: none"> • Dedicated central node • Limited spatial coverage • Single point of failure • Poor scalability, small number of nodes • Asymmetric power consumption (master consumes much more energy than the slaves) • Inefficient slave-to-slave communication
Mesh topology	<ul style="list-style-type: none"> • Distributed processing • Peer-to-peer communication • Very fault tolerant • Scalable • Large spatial coverage • Low/medium complexity • Energy consumption can be balanced among nodes 	<ul style="list-style-type: none"> • Nodes used must have same basic functionality, including routing capabilities • Complexity of routing • High latency and low bandwidth
Tree topology	<ul style="list-style-type: none"> • Low power consumption of leaf nodes • Large spatial coverage area • Scalable • Large spatial coverage • Medium complexity 	<ul style="list-style-type: none"> • Low reliability (node failure effects routing) • High latency and low bandwidth • Asymmetric power consumption (nodes in the tree backbone consume more) • Nodes used must have same basic functionality

3.2 MAC Protocols for Wireless Sensor Networks

3.2.1 Existing Standards

IEEE 802.15.4 is created for small devices of wireless personal area networks. The devices consume low power and have lower data rates. The protocol provides bit rates of 20 kbps, 40 kbps, and 250 kbps. The devices operate at the frequencies of 868 MHz, 915 MHz, and 2.45 GHz, respectively. IEEE 802.15.4 standard provides both star topology and peer-to-peer topology. There are two operation modes: beacon-enabled mode and non beacon mode. In the beacon-enabled mode, the network devices are synchronized to perform slotted CSMA. In the non beacon mode, the unslotted CSMA is adopted. A modified CSMA/CA algorithm is used by IEEE 802.15.4 to access the wireless channel. When a sensor device wants to send data, it performs a random back off before sensing the channel. For the unslotted CSMA/CA, if there is no activity on the channel, then the device transmits the data immediately. When slotted CSMA/CA is used, if the device detects no activity on the channel for two consecutive slots, it transmits the data. Any time a device detects activity during the contention section, it backs off for a random time and senses the channel at a later time.

To conserve energy, the coordinator does not initiate any data transfer. Fig. 3.2 shows the data transfers for two cases. If the sensor device data for the coordinator, it just transmit it. The coordinator then sends back an acknowledgment. If the data transfer

is from coordinator to device, the transfer can still only be initiated by the sensor device. The device sends a data request command to the coordinator. Then the coordinator transmits an acknowledgment followed by the data message. Finally, an acknowledgment is sent by the sensor device to the coordinator.

Fig. 3.2 IEEE 802.15.4 data transfer. (a) Data transfer to coordinator. (b) Data transfer from coordinator

Although IEEE 802.15.4 focuses on applications of the personal area networks, the standard does not clearly define the operation of devices in a peer-to-peer topology. And there is no efficient power saving scheme to support very low duty and energy constrained nodes.

3.2.2 Sensor Network MAC Protocols

Wireless MAC protocols proposed for other kinds of networks are not suitable for WSNs because of a lot of reasons. The most important reason is the power constraint.

To overcome the limited energy and processing resources on the sensor devices, the proposed MAC protocols must give the same performance at the cost of the smallest amount of energy consumption. There are mainly four reasons for energy waste in WSNs: collisions, idle listening, overhearing and overhead. For collisions, they limit the communication performance and cause energy waste. Energy waste further leads to significant decrease of sensor node's lifetime. Retransmitting a message consumes multiple times the energy required for the message. For sensor networks that do not require a reliable link, it is no need to retransmit messages, but the loss of data decreases the accuracy.

Overhearing refers to that the sensor nodes receive the message which is not intended for it. Those receivers, who overhear the message, waste energy on reception and data processing. MAC protocols can reduce overhearing but cannot eliminate it. However, MAC protocols can just use overhearing to get extra information about the wireless channel, such as how long the transmission among other sensor devices takes. Then the sensor node can enter sleep state for that period of time. A MAC protocol can also stop receiving and go into sleep once it finds out that the message is not intended to itself.

Idle listening is another case about energy waste. In this case sensor nodes listen for messages but no sensor node transmits at that time. Idle listening consumes much more power than in the sleep state. Normally MAC protocols limit idle listening by

using a timer to end reception and enter into sleep states if the sensor node does not detect any activity on the channel.

Overheads in MAC layer include synchronization messages, preambles and other control messages. The overheads do assist communication and improve the reliability of communication, but when the data packet is very small, which normally happens in sensor network applications, the overheads consume too much energy.

MAC protocols should perform the functionalities required by the application with the limited energy resources. The protocol designers must utilize the transceiver, the processor and sensors properly to conserve energy and prolong the network lifetime. Limited computation and storage resources are another constraint. MAC protocols must be simple enough to be put into the memory. A large amount of state and complex computation are not possible. But on the other hand, it has to be efficient and powerful enough to overcome the collision, idle listening, and overhead to save the power.

The most common method to reduce energy consumption is placing the transceiver into a sleep state when they have no data to transmit or receive. MAC protocols for WSNs may sleep for fixed durations periodically or sleep for random period of time. Although sensor nodes cannot do anything during sleep, it really can increase the lifetime dramatically. Duty cycle, which is defined as the fraction of time the sensor

node is awake, is always set below 1% in many WSNs applications in order to extend the network lifetime. Further energy conservation comes from multi-hop communication. Single hop MAC protocols may consume too much energy if a WSN is over a large geographical region.

Sensor network MAC protocols are classified into schedule based protocols and contention based protocols. For schedule based MAC protocols, the sensor nodes are coordinated to perform communications in an orderly manner. Time division multiple access (TDMA) is often adopted for schedule based MAC protocols where sensor nodes are assigned time slots to transmit or receive data. Organizing sensor nodes reduces collisions but has to maintain synchronization and share states. Contention based protocols allow sensor nodes to work independently with a minimum of complexity. Although collisions and idle listening may occur, normally the contention based MAC protocols do not need to share or maintain states. Some protocols, like LEACH [15] and GANGS [66], consider some other factors. They discuss the topology, which actually is beyond the MAC range, but influences MAC very much. In the following part, the details of several typical MAC protocols are discussed.

3.1.3.1 Contention based

Contention based MAC protocols offer the advantage of simplicity. They do not have to maintain and share states, therefore a contention based MAC protocol may consume fewer processing resources and less energy. Additionally, sensor nodes can

join into the network much more quickly. Contention based MAC protocols can adapt to changing traffic conditions more easily. However, contention based MAC protocols have a higher chance of collision, idle listening and overhearing.

B-MAC

The Berkeley MAC (B-MAC) protocol uses long preamble to wake up the sleeping neighbors [17]. In B-MAC sensor nodes follow sleeping schedules independently based on certain duty cycle. Since the sensor nodes operate independently, B-MAC uses quite long preambles so that the destination has enough time to wake up and sense activity. Sensor nodes that sense activity on the channel remain awake to receive the message which follows the preamble. Fig. 3.3 shows an example of message transfer in B-MAC. B-MAC relies on CSMA. Sensor nodes using B-MAC can join into the network once deployed. A sensor node can begin to send a message immediately once the channel is clear.

Fig. 3.3 B-MAC data transfer [12]

WiseMAC

Based on B-MAC, WiseMAC [67] further reduces energy consumption by remembering the sampling offsets of their neighbors. ACK packets have an extra field

which is used to notify the sender the time until next sampling. Once a sensor node receives this information, it only starts to transmit the preamble just before the receiver wakes up to sense the channel. WiseMAC decrease the preamble time duration and the number of overhearing sensor nodes at the cost of an extra field in the ACK messages and the memory which stores neighbor's sampling offsets. Fig. 3.4 shows the principle of WiseMAC.

Fig. 3.4 WiseMAC protocol. WUP is wake-up preamble. T_p is duration of WUP. T_w is wake-up period of destination [68].

3.1.3.2 Schedule based MAC protocols

Schedule based MAC protocols coordinate sensor nodes with a common schedule. According to the schedule, the sensor nodes coordinate to decide which sensor nodes can use the channel at a certain time. By this way, collisions, idle listening and overhearing are limited. Nodes which do not participate in the communication enter the sleep mode until they have data to transmit or receive. However, schedule based protocol increases the overhead to coordinate with each other. The mobility and node death make the schedule maintenance complicated. Sensor nodes must learn the

schedule first before joining in. Synchronization becomes an important issue for scheduled based MAC protocols. The periodic beacon increases the overhead and the clock shift may cause transmission failure. Additionally, some delay is introduced by schedule processing.

3.1.3.2.1. Self-calculated schedule based

TRAMA

The Traffic-Adaptive Medium Access (TRAMA) protocol [69] is proposed for energy efficient collision free channel access in WSNs. Energy efficiency is achieved by ensuring that unicast and broadcast transmission have no collisions and by allowing node to go into sleep when they are not transmitter or receiver at certain time. TRAMA uses a distributed election scheme to determine the transmitter at certain time. A node will be elected as the transmitter if it has the highest priority among its two-hop neighbors. The priority of a node at any time slot is defined as random function of its sensor ID and the number of the time slot. Using the traffic information, it avoids the case that the time slot is assigned to a node without data to send.

TRAMA has three components: the Neighbor Protocol (NP), which shares the topology information; the Schedule Exchange Protocol (SEP), which allows nodes to share two hop neighboring information and schedules; and the Adaptive Election Algorithm (AEA), which selects transmitters and receivers based on the topology, traffic conditions and schedules, and leaves the rest nodes to the sleep mode. The

node with the highest priority within a two-hop neighborhood owns the corresponding slot. Frames within TRAMA consist of random access period and scheduled access period. The random access control slots come at the beginning of a frame to perform NP and the scheduled data slots follows to perform SEP, AEA and data transmission.

TRAMA has several advantages. The random access period in the frame allows sensor nodes to quickly get the neighboring information. The scheduled access to the data slots limits the collisions. The scheduled protocol makes the nodes who are neither transmitter nor receiver go into sleep mode to save energy. TRAMA considers the traffic condition and groups the data slots which are given away at the end of the frame. However, TRAMA also has several disadvantages. First, TRAMA has a higher duty cycle than many other protocols. Sensor nodes need to be awake during the contention period which wastes energy. Secondly, TRAMA has a higher delay than contention based MAC protocols. This is a typical drawback of the schedule based protocols. Finally, similar to NAMA, TRAMA has a higher level of complexity. The protocol needs to maintain and update large amounts of state frequently on the node.

PMAC

Pattern MAC (PMAC) protocol is another self calculated schedule based protocol [70]. It adaptively determines the sleep schedules for a sensor node based on its own traffic and the traffic patterns of its neighbors. PMAC includes three parts: pattern generation, pattern exchange and schedule generation. In the beginning the sensor

node generates its own pattern based the traffic for next slot. If there is no data to send, it gives the pattern of the next a “0”. If it has data to send in the next slot, pattern is “1”. To accomplish the pattern exchange, the super time frame (STF) is divided into a pattern repeat time frame (PRTF) and pattern exchange time frame (PETF) as shown in Fig. 3.5. The neighbor nodes exchange their patterns during PETF. After the pattern exchange, sensor nodes will calculate their sleep-wakeup schedules. When the pattern bit for itself is “1”, if it has data to send and the pattern bit of the receiver node is also “1”, then the schedule bit is “1” which means that it will wake up during that slot. If the pattern bit of the receiver is “0”, the sensor node wake up at the beginning of that slot and listen for a certain period of time. It goes to sleep if it hears nothing. Otherwise it will receive data since it is the receiver. When the pattern bit of the sensor is “0”, only if it has data to send and the pattern bit of the receiver is also “1”, the schedule bit is assigned “1”. For the rest case the schedule bit will be given a “0”.

Fig. 3.5 Division of time frame for PMAC. STF is super time frame. PRTF is pattern repeat time frame. PETF is pattern exchange time frame. [22]

PMAC offers the quickly adaptation for changing traffic as well as low energy consumption. However, the algorithm has several disadvantages. First, there is no error control scheme if some sensor nodes do not receive the updated pattern due to bad channel condition while others receive the update. This introduces different schedules among neighborhood and cause collisions or idle listening. Second, the algorithm is somehow complex. It will be difficult to implement for the sensor node with limited memory and processing resources.

3.1.3.2.2. Time slot assignment MAC

TDMA is a good choice for MAC protocols of WSNs by reducing collisions and idle listening. Fairness and simple traffic engineering also become. Several drawbacks arise at the same time. Time slot assignment becomes difficult because sensor nodes cannot coordinate without introducing large overhead. Synchronization functionality is necessary to correct clock shift for each sensor node. If the traffic load is light, TDMA protocols suffer from utilization problems. Below are some typical TDMA based MAC protocols proposed for WSNs.

SMAC and variants

SMAC [14] is one of the most studied MAC protocols for WSNs. It synchronizes the sleep schedules among the neighboring nodes. Sensor nodes wake up and communicate in the active period and go to sleep in the sleep period. They use the RTS/CTS scheme to transmit messages during the active period of the frame (Fig.

3.6). The sensor node who receives CTS transmits message during the inactive period.

If sensor nodes hear an RTS or CTS message for another node, they just go into sleep state to conserve energy. RTS and CTS messages contain the duration of message and the uninvolved sensors can sleep until that data transmission finishes.

Fig. 3.6 SMAC frame format

At the beginning of the frame, the sensor nodes send SYNC message. The other sensor nodes learn their neighbors' schedules from the SYNC messages, based on which they wake up in the future at the proper time to send their messages. There are several cases for sensor nodes to adopt the schedule from their neighbors. If a sensor node does not have a schedule and it hears a SYNC message, then it adopts the schedule. If a sensor node hears more than one schedule, it adopts all of them. If a sensor node does not hear any SYNC messages, it sets up its own schedule.

SMAC has several advantages. First, loose synchronization minimizes the coordinating for communication. Sharing beacon generation distributes the energy consumption evenly throughout the whole network. Second, SMAC is scalable. It does not require a whole network coordination. Third, the beacon is not large, so it will not cause large overhead. However, SMAC also have some disadvantages. First, sensor nodes may adopt multiple schedules. This would increase the duty cycle and

the nodes may die faster. Another disadvantage is the static duty cycle. It would be better if the duty cycle can be changed according to the traffic conditions.

SMAC has several variants. DSMAC adopts changeable duty cycles based on the traffic conditions and energy considerations [71]. In the SYNC message, a new field is added. If the traffic is heavy, the value of this field increases to increase their duty cycle. If the traffic is light, then the value of this field decreases. When the duty cycle is increased to obtain the average lower message latency, the energy consumption is increased at the same time because of the longer active time. Fig. 3.7 shows the DSMAC frame format with different duty cycle.

Fig. 3.7 DSMAC frame format with different duty cycle

T-MAC uses a timer to indicate the end of the data transmission instead of using a fixed duty cycle [13]. (Fig. 3.8) The sensor nodes save energy consumption by reducing the time duration they spend in idle listening and also adapt to changes of traffic conditions. If no active event occurs for time threshold T_A , the node will stop listening and go to sleep. To improve message latency, a future request to send

message (FRTS) is introduced which can be used by sensor nodes to inform the next hop node that it has another message to transfer.

Fig. 3.8 T-MAC protocol scheme with adaptive active time. TA is the threshold. If no active event occurs for time threshold TA, the node will stop listening and go to sleep.

MSMAC protocol focuses on the mobile sensor networks [72]. Sensor nodes estimate the movement of the neighboring nodes. Based on the estimation they increase the wakeup duration to decrease the joining time. To estimate the movement of sensor nodes, each sensor node records the RSSI values from its neighbor. Within each SYNC message the sensor node lists the maximum estimated speed among the neighbors. Sensor nodes with a high moving speed check for schedules more frequently and adopt schedules more quickly. The disadvantage is that MSMAC sacrifices energy consumption for faster synchronization.

Z-MAC

Z-MAC offers a more flexible TDMA protocol [73]. It combines the strength of TDMA and CSMA while on the other hand offsets their weaknesses. When the

contention is low, Z-MAC works like CSMA to achieve high channel utilization and low latency. If the contention is high, Z-MAC performs like TDMA. The high channel utilization can also be obtained. Collision can be reduced among two-hop neighbors at a low cost.

At the setup phase, neighbor discovery, slot assignment, local frame exchange and global time synchronization are conducted. The sensor nodes get the two-hop neighbor list by broadcasting its own one-hop neighbor list to one-hop neighbor. Then this two-hop neighbor list is used for distributed time slot assignment. The algorithm can ensure that there is no transmission interference within the two-hop neighbors. Local framing is adopted therefore it is no need to have the frame synchronization for the entire networks. Local neighbors have the same slot number. The time synchronization is done globally only once in the beginning.

For the data transmission, the slot owner has the priority than the non slot owner. If a slot does not belong to any owner or the owner has no data to send, the non owner can use this slot to transmit data. Z-MAC follows the techniques used in B-MAC including backoff, channel clear assessment and low power listening. Z-MAC also uses explicit congestion notification (ECN) messages to limit the hidden terminal problem for high contention situation.

Z-MAC achieves several benefits with the cost of protocol overhead. Maintaining the TDMA schedule and using ECN messages all consume certain amount of energy. The algorithm used in Z-MAC also challenges the processing ability of the sensor nodes.

3.1.3.3 MAC protocols with some other factors

For MAC protocol analysis, researchers always add some topology information into consideration. The topology information can influence the medium access quite a lot. Clustering sensor nodes provides several advantages. Cluster can be viewed as a single entity. Functionalities such as synchronization can be performed within a cluster. By this way, there is no need to share state information globally which takes longer time and larger energy consumption. The disadvantage is that control overhead increases. LEACH and GANGS are two typical clustering MAC protocols for WSNs.

LEACH

Low-Energy Adaptive Clustering Hierarchy (LEACH) provides a MAC protocol along with cluster based routing algorithm for data aggregation sensor networks [15]. The reason to form cluster infrastructure is that for the environment monitoring application, data from individual sensor node are often correlated with each other. The end user does not need these redundant data. The nodes with high correlation form a cluster and perform data processing within the cluster to reduce redundancy, and then transmit to the end user.

LEACH groups sensor nodes into clusters with one node acting as the cluster head. All non cluster nodes transmit their data to the cluster head, while the cluster head performs processing functions and forwards to remote BS. To evenly distribute the energy consumption of all the sensor nodes throughout the network, LEACH rotates the cluster head role among the sensor nodes within a cluster.

In the cluster formation section, the cluster head transmit a message to accept its role. Once the other sensor nodes receive the cluster head announcement, they send a join in message to the cluster head. If the sensor node receives multiple announcements, it selects the cluster head that requires the lowest energy for communication. The cluster head computes the schedule and distributes it to all the cluster members. Fig. 3.9(a) shows the communication architecture in the LEACH protocol.

Fig. 3.9 LEACH and GANGS communication comparison. (a) LEACH communication; (b) GANGS communication. [12]

LEACH centralized (LEACH-C) is a variant of LEACH which uses a central control algorithm to form the cluster. During the setup phase each sensor node sends its current location and energy levels to the BS. The BS computes the optimal selection of clusters for energy savings.

GANGS

The GANGS protocol [66] is also a cluster based TDMA MAC protocol. It is also designed for the data gathering application. To avoid this bandwidth waste and contention, the sensor network is divided into clusters. Each cluster owns a cluster head. Nodes within the cluster only communicate with the cluster head. The cluster heads form the backbone of the network and forward data to the BS. Contention free TDMA slots are adopted for the cluster head communication. Contention slots are used within clusters. Fig. 3.9(b) shows the communication mechanisms in GANGS. During the contention free slots, the non cluster head nodes turn off their radio to save energy. The cluster heads turn on the radio all the time. The cluster head role is rotated among all the sensor nodes.

Similar to LEACH, GANGS has the disadvantage of energy consuming for cluster formation and restructuring. The slot organization in GANGS also introduces resource waste since not all the slots are used if traffic changes. Another disadvantage is that because the cluster head's radio is always on, it will deplete its energy very fast.

3.2.3 Summary

Table 3.2 gives a summary of the MAC protocols for wireless sensor networks. According to the survey about the MAC protocols for WSNs, MAC protocol is a very important part for wireless sensor networks. It has to not only resolve the severe radio interference due to the shared medium, but also eliminate or reduce collision, overhearing, idle listening, and overhead to save the energy consumption. Fig. 3.10 shows the functionalities of MAC protocol for WSNs. the basic function is to successfully access the shared medium using TDMA/FDMA/CDMA/CSMA. The error control and the QoS improves the reliability for accident occurring. Energy efficiency is important for the power limited sensor nodes. Multi-hop communication and periodical sleep can reduce the power consumption. Based on this, researchers further reduce idle listening and overhead to improve the energy efficiency.

Fig. 3.10 Functionalities of MAC protocols

MAC protocols are classified into contention based MAC protocol and schedule based MAC protocol. Contention based MAC protocol normally bases on CSMA. All the sensor nodes contend for channels. The advantage of contention based MAC is simplicity, quick to participate, using few resources, etc. While it has to face collision, idle listening, and overhearing which waste a lot of energy. Scheduled MAC protocol allocates the communication channels to the sensor nodes. It eliminates or reduces the collision, idle listening, and overhearing problem, but it increase the overhead. The MAC protocol designers need to balance the advantages and disadvantages of these two kinds of protocol and design a suitable protocol for certain specified application.

Table 3.2 Summary of the MAC protocols for wireless sensor networks

Mac protocol name	Time SYNC?	Type	Specifics	Adaptable to mobility	Contention based or Schedule based?	Central coordinated or Distributed?	year	author
802.15.6	Yes/No	Slotted CSMA / TDMA / unslotted CSMA	Star, peer – peer	No	Contention / Schedule	Central	2011	
SMAC	Yes	Slotted CSMA	Sleep schedule	Yes	Contention		2002	W. Ye
T-MAC	Yes	Slotted CSMA	SMAC variant.	No	Contention		2003	T. van Dam
DSMAC	No	Unslotted CSMA	SMAC variant. Consider traffic	Yes	Contention		2004	P. Lin
MSMAC	Yes	Slotted CSMA	mobility	Yes	Contention		2004	H. Pham
B-MAC	No	Unslotted CSMA	preamble	No	Contention		2004	Joseph Polastre
WiseMAC	No	Unslotted CSMA	Similar to B-MAC	No	Contention		2003	A. El-Hoiydi
AC-MAC	Yes	Slotted CSMA	SMAC variant	No	Contention		2004	A. Jin
NAMA[74]	Yes	Slotted TDMA	Self calculates schedule	No	Schedule	Distribute	2001	L. Bao

TRAMA	Yes	Slotted CSMA / TDMA	Random access+schedule access, like 15.4	yes	Contention / Schedule	Distribute	2003	V. Rajendran
PMAC	Yes	Slotted CSMA / TDMA	traffic	Yes	Schedule	Distribute	2005	T. Zheng
EMACS[75]	Yes	TDMA	Control msg within slots	Yes	Schedule	Distribute	2004	L.F.W. van Hoesel
LMAC	Yes	TDMA	Similar to EMACS	Yes	Schedule	Distribute	2004	S. Chatterjea
AI-LMAC[76]	Yes	TDMA	LMAC variant	Yes	Schedule	Distribute	2004	S. Chatterjea
ZMAC	local	CSMA / TDMA	traffic	No	Contention / Schedule	Distribute	2005	I. Rhee
DMAC	Local	CSMA	Tree topology	No	Schedule	Distribute	2004	Gang Lu
LEACH, LEACH-C	Yes	CSMA / CDMA	BS-head CSMA, head-node CDMA. Both star topology	Not good	Contention / Schedule	central	2002	W. B. Heinzelman
GANGS	Yes	CSMA / TDMA	Intra cluster CSMA, TDMA for cluster heads	Not good	Contention / Schedule	Distribute	2004	S. Biaz

3.3 MAC protocols for Body Sensor Networks

Body Sensor Networks (BSNs) typically consist of multiple sensor nodes attached to the body surface or implanted into tissue, each capable of sampling, processing and communicating wirelessly. The physiological parameters are typically blood glucose and oxygen levels, pulse rate, blood pressure, temperature, image, etc. (Table 3.3). Antenna components in the sensor nodes make it possible for the data generated to be transmitted to a body-worn data collector wirelessly. The data collector receives the data generated from the various sensor nodes and process the data locally, transmit it wirelessly via an appropriate radio link for centralized processing, display and storage [77]. To realize prolonged monitoring and seamless integration into a BSN, wireless sensor nodes must meet requirements such as light weight, low cost, low power consumption, etc...

Table 3.3 Sensing Activities in BSNs [2]

Wearable devices	Implantable devices
EEG	Glucose sensor; Cardiac
ECG	arrhythmia
SpO2 pulse oximeter	Pacemaker; Cardioverter;
Glucose	Defibrillator
Fall detection	Intracranial pressure sensing
Emergency call	Wireless capsule drug delivery
Performance	Deep brain stimulation
assessment	Retinal sensors; Parkinson's;
	Epilepsy
	Insulin pump

There are many applications of BSNs. CodeBlue uses several sensors, such as pulse oximeter, ECG, etc. to collect body parameters and sends wirelessly to AP.

Husemann et al. considered to combine health-related wearable devices with PDA devices [78]. Espina et al. used BSN for monitoring continuous blood pressure [79]. An “electronic patch” included pulse oximetry and electromyography sensors proposed by Haahr et al. [80]. Many transceivers are manufactured for the low power, short distance communication for health care applications (Table 3.4).

Table 3.4 Transceivers for healthcare applications

Chip	Company	Frequency (MHz)	Tx current	Rx current	Tx power	Modulation scheme	Data rate (kbps)
CC1110	Texas Instruments	433	15.2mA	16.2mA	-20dBm, 10dBm	FSK/MSK	500
ZL70102	Zarlink	402-405/ 433-434	5mA	5mA	-3dBm	FSK/4FSK	800
TDA525X	Infineon	315/434/ 868/915	11.9-14.1mA	8.6-9.3mA	-32dBm, 13dBm	FSK/ASK	64
AT86RF212	Atmel	700/800/900	17mA	9.2mA	-11dBm, 5dBm	PSK/QPSK	1000
SX1233	Semtech	433/868/915	20mA	17mA	-18dBm, 17dBm	FSK	600

Star topology and mesh topology are the most commonly used topologies for BSNs.

Star topology makes a point to point link which has a simple design and low latency.

For mesh topology, there are typically multi-hop links between nodes and each node has its own path through the network to the destination. One advantage of the mesh

topology is that it utilizes the bandwidth more efficiently. Mesh networks are also fault tolerant, as multiple paths let the network handle individual node failures easily.

Although BSNs are similar to WSNs in many ways, there are still differences between them. Some of these differences are illustrated in Table 3.5.

Table 3.5 Different challenges faced by WSNs and BSNs

Challenges	WSNs	BSNs
Scale	As large as the environment being monitored (meters/kilometers)	As large as human body parts (millimeters/centimeters/meters)
Node Number	Greater number of nodes required for accurate, wide area coverage	Fewer, more accurate sensors nodes required (limited by space)
Node Accuracy	Large node number compensates for accuracy and allows result validation	Limited node number with each required to be robust and accurate
Node Size	Small size preferable but not a major limitation in many cases	Pervasive monitoring and need for miniaturisation
Dynamics	Exposed to extremes in weather, noise, and asynchrony	Exposed to more predictable environment but motion artefacts is a challenge
Data Protection	Lower level wireless data transfer security required	High level wireless data transfer security required to protect patient information
Power Supply	Accessible and likely to be changed more easily and frequently	Inaccessible and difficult to replace in implantable setting
Power Demand	Likely to be greater as power is more easily supplied	Likely to be lower as energy is more difficult to supply
Access	Sensors more easily replaceable or even disposable	Implantable sensor replacement difficult and requires biodegradability
Biocompatibility	Not a consideration in most applications	A must for implantable and some external sensors. Likely to increase cost
Wireless Technology	Bluetooth, Zigbee, GPRS, and wireless LAN, and RF already offer solutions	Low power wireless required, with signal detection more challenging
Data Transfer	Loss of data during wireless transfer is likely to be compensated by number of sensors used	Loss of data more significant, and may require additional measures to ensure QoS and real-time data interrogation

The IEEE 802.15.6 group concentrates on body area networks for medical devices. The initial study are for very low-power devices and sensors and wish to obtain a single standard with a broad range of data rates. According to the IEEE 802.15.6's first report and draft [81], BSNs should operate on, inside or around the body with a limited range ($<0.01\text{--}2\text{ m}$). The channel model should consider human body effects, including absorption and health effects. An extremely low consumption power ($0.1\text{--}1\text{ mW}$) is required for medical devices. The BSNs should support a wide range of data rate ($0.01\text{--}1000\text{ kbps}$, optional 10 Mbps). Sensor devices would support for different classes of QoS for high reliability, asymmetric traffic and power-constrained scenarios.

The protocol supports six frequency bands: $402\text{--}405\text{ MHz}$, $420\text{--}450\text{ MHz}$, $863\text{--}870\text{ MHz}$, $902\text{--}928\text{ MHz}$, $950\text{--}956\text{ MHz}$, $2360\text{--}2400\text{ MHz}$ and $2400\text{--}2483.5\text{ MHz}$. $402\text{--}405\text{ MHz}$ is the frequency for legal medical implant communications service (MICS). Compared to other available frequencies, the $402\text{--}405\text{ MHz}$ frequency band best meets the technical requirements of the MICS for a number of reasons. The $402\text{--}405\text{ MHz}$ frequencies have propagation characteristics conducive to the transmission of radio signals within the human body. In addition, equipment designed to operate in the $402\text{--}405\text{ MHz}$ band can fully satisfy the requirements of the MICS with respect to size, power, antenna performance, and receiver design. Further, the use of the $402\text{--}405\text{ MHz}$ band for the MICS is compatible with international frequency allocations. Finally, the use of the $402\text{--}405\text{ MHz}$ frequency band for the

MICS does not pose a significant risk of interference to other radio operations in that band.

The structure of the Physical-layer Protocol Data Unit (PPDU) defined by the 802.15.6 is shown in Fig. 3.11. During the transmission, the physical-layer service data unit (PSDU) will be pre-appended with a physical layer convergence protocol (PLCP) preamble and header to create a PPDU. At the receiver side, the PLCP preamble and header serve as aids in the demodulation, decoding and delivery of the PSDU.

Fig. 3.11 IEEE 802.15.6 physical layer frame structure.

The data frames are exchanged between nodes and hubs. The hubs are responsible for coordinating channel access. There are three modes for accessing: beacon mode with beacon period superframe boundaries, non-beacon mode with beacon period superframe boundaries and non-beacon mode without beacon period superframe boundaries. Fig. 3.12 shows the structure of beacon mode with beacon period boundaries. The beacon comes in the beginning of the frame followed by two

consecutive periods each consisting of an Exclusive Access Phase (EAP), Random Access Phase (RAP) and Type-I/II access phase. The hub may set to zero the length of any of these access phases. To provide a non-zero length CAP, the hub shall transmit a preceding B2 frame.

Fig. 3.12 Beacon mode with beacon period boundaries superframe structure.

IEEE802.15.6 provides macroscopic and microscopic power management schemes named hibernation and sleep. To hibernate, the sensor nodes can sleep for n consecutive beacon periods by setting the Wakeup Period field in its last connection request frame an integer n and set the Wakeup Phase field a value identifying the intended next wakeup beacon period. Within the beacon frame, a node should wake up to receive and transmit packets in its scheduled allocations. Outside the expected allocations, the node goes into sleep for energy conservation.

There are also some MAC protocols for BSNs proposed by researchers all over the world. The limited contained energy requires the network to be much efficient to obtain a long network life time. Here, a survey of MAC protocols for BSNs is given.

Star topology

Marinkovic et al. proposed an energy efficient MAC protocol for remote monitoring

of physiological signals such as EEG and ECG [17]. The protocol takes advantage of the static nature of the BANs to implement an effective TDMA scheme with little amount of overhead. The communication topology is given in Fig. 3.13. Fig. 3.14 shows the timing diagram of the TDMA frame. The time slots are allocated to different sensors. Extra slots are reserved for packet retransmission in case of communication errors. A guard time duration is inserted between every two consecutive slots. The last section is used for data transmission to the monitoring station. From the point of view of energy efficiency, it is the same as IEEE802.15.6. The sensor node only wakes up at its own slot to transmit or receive data. In the rest slots it goes into sleep to save energy. The slot assignment is calculated by the coordinator.

Fig. 3.13 Topology for body sensor networks. S is sensor node. MN is master node. MS is monitoring station [17]

Fig. 3.14 Timing diagram of the TDMA frame by Marikovic et al. [17]

Zhang Yan et al. proposed a MAC protocol for BSNs consisting of both medical applications and consumer electronics (CE) applications [82]. Fig. 3.15 shows the frame structure. There are two CFP data channel: TSRP which is time slot reserved for periodic traffic and TSRB which is time slot reserved for burst traffic. Two CAP control channels, AC1 and AC2, are used for medical uplink control and CE uplink control.

Fig. 3.15 Frame structure of the priority guaranteed MAC protocol [82]. CFP is collision free period. CAP is collision access period. TSRP is time slot reserved for periodic traffic. TSRB is time slot for burst traffic.

For this MAC protocol, the frame structure is adaptive. The control channels are reserved on a regular basis, but the data channels are assigned on demand. Because

the control channel is much shorter than the data channel, the cost is relatively low. Besides, the overhead for the control channel is optimized to be adaptive to the traffic load. The scalability is illustrated in Figure 3.16. (1) and (2) show the case that there is only one type of traffic, either the periodic traffic or the burst traffic, in the network. (3) indicates the case that there is no active traffic. The control channels can be adjusted to the minimum size to improve the resource efficiency. This MAC protocol also has similar energy efficiency as TDMA based MAC protocol.

Fig. 3.16 Illustration of frame structure scalability [82].

Yoo et al. proposed a “pulling” MAC protocol [83]. For WSNs and BSNs, sensors periodically send data to the coordinator. A contention based MAC protocol has low channel utilization and low data throughput, while a schedule based MAC protocol has a large overhead. A “pulling” MAC protocol is proposed to overcome the above drawbacks. The coordinator transmits command to ask the data from the sensors. The sensors then send the corresponding data to the BS in a passive way. There is no need

for synchronization but the schedules are controlled by the coordinator. A reliable communication can be achieved. However, the “pulling” MAC protocol may be not suitable for BSNs since it requires sensor nodes to listening all the time without sleep. This will consume quite a lot of energy.

Omeni et al. proposed a star topology MAC protocol for BSNs [16]. All the communications are single hop. Clear channel assessment and collision avoidance with TDMA is adopted. The access scheme significantly reduces collision and idle listening, therefore leads to significant power savings. In addition, time slot allocation is dynamically controlled by the master node, so the time slot assignment for slave node could be changed every time it communicates with the master. This enables the system to the tackle changing traffic situation.

A concept of wakeup fallback time is proposed to deal with time slot overlaps. If a slave wakes up but unable to communicate with the master, then it goes back to sleep with a timer. During this time it buffers the sensing data. After the timer is up, it wakes up and searches for the master. Similarly, if the master is unable to communicate with the slave node at the wakeup time, it goes into sleep status and start the fallback time. This scheme ensures that time slot overlaps can be coped with and do not sacrifice the network performance in the long run. It saves energy by going into sleep mode if a designed communication fails.

Timmons et al. proposed a MAC protocol, called “MedMAC”, mainly discussing about the dynamic synchronization scheme [2]. Most of the contents are similar to other protocols. All devices go to sleep when not transmitting or receiving. Within each super frame, data slots are allocated to devices by the coordinator. The main features of the protocol are maintaining synchronization without waking up for regular beacons and Adaptive super frame structure.

Fig. 3.17 Guard bands of MedMAC [2]

The MedMAC relies on synchronization between the coordinator and sensor nodes. For low power wireless networks, waking up to listen for a beacon consumes a significant drain on energy in a sensor node. MedMAC introduces a synchronization mechanism where the node can sleep through a number of beacon periods without losing synchronization. Maintaining synchronization while sleeping through beacons

is realized by adopting timestamp scavenging and an Adaptive Guard Band Algorithm (AGBA). In timestamp scavenging, synchronization can be maintained by using an updated timestamp field as long as packets are sent from the coordinator to a node. However, if due to some reason, there is an interruption in the delivery of packets from the coordinator, then the node cannot rely on scavenging packets from the BS to maintain the schedule. In this case, the AGBA allows the sensor node to go to sleep without losing synchronization with the coordinator. It does so by introducing a guard band for each of the timeslots as shown in Fig. 3.17. The Drift Adjustment Factor (DAF) minimizes the bandwidth waste using this guard bands. The nodes go to sleep and are updated with new timing corrections by capturing the beacon in the beginning of the next super frame. Compared with most TDMA based MAC protocols, MedMAC gives sensor nodes most sleep time by self calculated synchronization without waking up to listen to beacon.

Li Huaming et al. proposed a heartbeat driven MAC protocol for BSNs [84]. The heartbeat rhythm information is instead of periodic beacons. Heart beat rhythm is inherent in the human body and can be obtained from various biosignals. Biosensors can extract the heartbeat rhythm from sensing data by detecting waveform peaks. All rhythms are naturally synchronized because of the same driven source. By following the rhythm, biosensors can maintain synchronized without turning on the radio to receive the synchronization information from the coordinator. The idea sounds reasonable, but the feasibility is a big challenge. First, the sensors have extra

components to receive the heartbeat signal. Whether it is really energy and resource efficient is a question. Second, making the rhythm signal acquisition system small and accurate is not easy.

Su Hang et al. consider the battery dynamics, the wireless channel qualities, and the queuing characteristics into the MAC protocol design [85]. The proposed MAC protocol is based on a star topology TDMA. The battery dynamics means that the batteries have the ability of recovering the initial value of the voltage when they remain idle for a certain period of time, which is called battery's recovery capacity effect. Based on this, the proposed MAC protocol tries to maximize the idle periods.

Fig. 3.18 System architecture of battery dynamic MAC protocol [85]

The system architecture of our proposed schemes is shown in Fig. 3.18. A finite-length first-in-first-out (FIFO) buffer is deployed at the sensor nodes. If the buffer of the sensor is full, the new coming packets will be dropped. The queues are processed at the adaptive modulation module, and transmitted into the air. The

adaptive modulation is for maximizing the data rate by adjusting transmission parameters to the available channel state information (CSI), while maintaining a predetermined BER. The sensor nodes estimate CSI by analyzing the received signal strength of the beacon. The received CSI and the queue length information are used together to control the adaptive modulation module when deciding the packet transmissions data rate. The main challenge is that the queue and adaptive modulation scheme would utilize the limited energy and processing resources.

Mesh topology

HyungTae et al. proposed an energy efficient multi-hop communication in body area networks [86]. A minimum spanning tree (MST) routing is adopted for the multi-hop network. The coordinator constructs the MST using battery status of sensor nodes as well as the distance. Because the nodes consume power due to data transmission, the MST has to be reconstructed. For reconstructing the MST, every node sends the ratio of the initial battery power to the remaining power to the coordinator periodically. Each node waits for a certain period of time after receiving the information about the reconstructed MST, which is broadcasted by the coordinator. The node sends its remaining power, E_i , to the coordinator when sending its data during the allocated time slots. If E_i is smaller than the certain threshold for the node i , the node sends a Topology_Control request message to the coordinator and the coordinator rebuilds an MST. To tackle the heterogeneous data gathering more efficiently, dynamic time slot allocation is proposed as shown in Fig. 3.19. The coordinator will assign different slot

size for different sensors. This proposal does not mention adaptive transmit power which could make the communication more energy efficient and obtain a longer network lifetime. Also just due to this, the protocol could not deal well with mobile scenario.

Fig. 3.19 Dynamic time slot allocation [86]

Maman et al. pointed out that the key requirements in BSN applications include low power consumption, high reliability, and low latency [87]. Multi-hop communication is used for relaying data to the coordinator. A super frame structure is proposed as shown in Fig. 3.20. The beacon is sent periodically to the sensor devices by the coordinator. Then the sensor devices send back an acknowledgment packet to the coordinator in the indicator slots. During the monitoring section, the sensors follow the schedule to send data to the coordinator.

Fig. 3.20 Super frame structure of the multi-hop MAC proposed by Maman et al.

Because the coordinator knows that if the data transmission in the monitoring period succeeds or not from certain devices, the performance can be improved by learning methods including prediction criteria. The coordinator can analyze the packet error rate (PER) and assign some additional relays. The decision would depend on a prediction model of the link reliability and a variable which can be evaluated within the current frame. The coordinator calculates the best route for each BAN device and informs this procedure through beacons. With this solution, the attribution of relaying functionalities is allocated by the coordinator. Prediction of the link reliability is based on the statistical analysis of the receiving data in the Monitoring Period. If the ratio of successful reception is smaller than 90% or the last reception failed, the coordinator can decide to assign some specific relays. This proposal do have a dynamic routing mechanism to react against the change of the channel, but it uses PER of the real monitoring data and this will cause lost of monitoring results. Adaptive power control could be considered here to further reduce the energy consumption.

Miscopein et al. proposed a preamble sampling based MAC protocols for BAN [88].

It limits the cumulative emission duration of a node. A cooperative preamble over a

set of nodes is proposed as shown in Fig. 3.21. The source node sends a burst. It indicates the coming transmission of a data packet at a given time. This burst data is relayed one time after another by nodes who wake up during a burst. At last, the destination node wakes up at one of the relays and learns the time left before data. According to this value, the node could go back to sleep and wake up at the right time to receive the data.

Fig. 3.21 CoMAC principles of burst relaying [88]

To cope with the case that multiple nodes wakes up during a relay, a priority for relaying data is given out. Node that has detected a burst gives a random back-off (δ). At the end of the burst it sets a timer equal to δ and starts listening to the channel. If it detects that another node starts relaying before the end of the timer, it goes to sleep mode; otherwise it relays the burst (Fig. 3.22).

Fig. 3.22 CoMAC relaying collision avoidance [88]

CoMAC is a fully distributed algorithm without a central coordinator. The transmit power has to be large enough for a mobile case. Both distributed routing and preamble consumes a relatively large amount of energy. Since there is a time gap between the preamble and the real packet transmission, latency may be quite large, which is a disadvantage.

The MAC protocols for BSNs are reviewed in this part. The specific attributes of human body is considered and the medium access control mechanism is discussed for satisfying the requirement of low power consumption, low latency, and high reliability. The QoS, such as traffic classification, battery dynamics, priority, is analyzed. A summary is shown in Table. 3.6.

Different medium access scheme and schedules are proposed. They optimize one or more aspects of the medium access. Some are easy to implement, and some may be

not that easy. It is hard to say that one protocol outperforms than another for all the aspects. We are going to propose a novel MAC solution mainly focusing on reducing the energy consumption of sensor devices by giving them more sleep time, less control overhead, and multi-hop communication. The proposed MAC protocol will be compared with 802.15.6 draft. The details will be discussed in Chapter 4.

3.4 Summary

This chapter gives a comprehensive review on MAC protocols for WSNs and BSNs. The network topology, existing standards are discussed. After analyzing the constraints of the network design, the recent proposed MAC protocols are reviewed in detail. In the Chapter 4, a novel MAC protocol will be proposed for multiple capsule networks on the basis of these literatures

Table 3.6 Summary of the MAC protocols for body sensor networks

author	Time SYNC?	Topology	Type	Specifics	Adaptable to mobility	paper name	year
Marinkovic	yes	centralized	TDMA	basic function	no	energy efficient low duty cycle MAC protocol for wireless body area networks	2009
Omeni	Yes	centralized	TDMA	Clear channel assessment; error control for slot overlapping by wakeup fallback time	no	Energy efficient medium access control for wireless medical body area sensor networks	2008
HyungTae	Yes	distributed	sloted CSMA /TDMA	multi-hop communication; dynamic slot duration		Energy efficient multi-hop transmission in body area networks	2009
Otal [89]	Yes	centralized	TDMA	complicated. Not easy to implement. Simulation results only.		Highly reliable energy saving MAC for wireless body sensor networks in healthcare systems	2009
Timmons	yes/no	centralized	TDMA	adaptive guard band to let the sensors not necessary to wake up for every beacon	no	An adaptive energy efficient MAC protocol for the medical body area network	2009
Li Huaming	no need	centralized	TDMA	use the rhythm instead of the synchronization information	no	Heartbeat driven medium access control for body sensor networks	2010
Su Hang	yes	centralized	TDMA	battery dynamic, consider wireless channel quality, use buffer	no	Battery-dynamics driven TDMA MAC protocols for wireless body-area monitoring networks in healthcare applications	2009

Yoo	no	centralized	pulling, collision free	BS pulls data from sensors. BS controls all the schedules		Low complexity, high throughput multiple access wireless protocol for body sensor networks	2009
Maman	yes	multi-hop	TDMA	multi-hop; route based on the PER	yes	BATMAC: An Adaptive TDMA MAC for Body Area Networks Performed With a Space-Time Dependent Channel Model	2011
Ameen	yes	centralized	TDMA/slotted aloha	QoS:classify the traffic and device;radio triggered hardware		A Power Efficient MAC Protocol for Implant Device Communication in Wireless Body Area Networks	2011
Miscopein	no	distributed	contention based	good paper; not consider the BAN special attributes; discuss protocols in details	no	Cooperative beacon-free MAC layer for Body Area Networks	2009
Hussain	yes	centralized	hybrid	directional antenna; two coordinator;	no	TDMA Based Directional MAC for WBAN	2010
Yoon	yes	centralized	hybrid	traffic classified; priority; optimization of TDMA frame	no	PNP-MAC: Preemptive slot allocation and Non-Preemptive transmission for Providing QoS in Body Area Networks	2010
Zhang Yan	yes	centralized	TDMA	priority guaranteed by allocating specific control data and differentiating type of traffic; frame structure is flexible for high scalability		A New Priority-guaranteed MAC Protocol for Emerging Body Area Networks	2009

Gengfa Fang						BodyMAC: Energy Efficient TDMA-based MAC Protocol for Wireless Body Area Networks	2009
review papers							
Kwak				good review		a study on proposed IEEE 802.15 WBAN MAC protocols	2009
Ullah				not bad		on phy and mac performance in body sensor networks	2009
Ullah						a study of medium access control protocols for wireless body area networks	2009
Gopalan						Energy-Efficient MAC Protocols for Wireless Body Area Networks: A Survey	2010
Kutty				bad paper		Towards Energy Efficient Protocols For Wireless Body Area Networks	2010
Ali				QoS; differentiate priority; writing not clear to show the idea		urgency based mac protocol for wireless sensor body area networks	2010
Ruzzelli		distributed	hybrid	not limited to body area network.		Energy-efficient multi-hop medical sensor networking	2007

Chapter 4 Energy Efficient MAC Protocol for Multiple Capsule Networks

4.1 Introduction and Motivation

With the advancement of capsule technology brought about by various research aspects, we can expect various types of capsules of different functionalities to be available in the near future. It is also envisaged that a patient ingests more than one capsule over a short period of time, and these capsules will cooperate, in-vivo, to complete a single coordinated objective (Fig. 4.1). The wireless capsule devices, together with the coordinator, form a wireless network.

Fig. 4.1 Multi-capsule network architecture

For this novel multi-capsule system, the network topology, communication protocols, and control system requirements are challenging research issues that need to be resolved. These challenges for multi-capsule network are different from those

explored for commonly used wireless networks. The miniature size and the in-vivo operating conditions of the capsule requires novel networking protocols and algorithms to be developed such that a network of capsules would be able to cooperate wirelessly given the extremely limited energy, processing and memory resources on each capsule.

Power supply is a big challenge for the multiple capsule networks. The current capsule devices are powered by two 1.5V, 80 mAh button batteries. It can last 8 hours to perform only the basic function of capturing and transmitting images with a frame rate of 2 frames/second. If a real time image transmission is required or other functionalities such as drug delivery, active locomotion is added, the power supply is far from enough. However, from the other side, the advances in battery technology are much slower than the recent advances that have taken place in the field of wireless communications and networks. But due to the potentially life threatening situations, the reliable delivery of vital body parameters is very critical requirement of patient monitoring. Therefore, efficiently utilizing the limited battery power and prolonging the lifetime of the network is an important issue.

It is well known that the radio transceiver consumes quite a large amount of energy of the sensor nodes, and a good MAC protocol can efficiently reduce the energy consumption of the transceiver, therefore, designing energy efficient MAC protocols for the BSNs and multiple capsule networks is necessary.

Many MAC protocols are proposed for WSNs and BSNs by researchers. However, multiple capsule networks have its own attributes which makes it different from WSNs and BSNs. A few attributes for the multiple capsule networks are listed as follow:

- Multiple capsule networks are composed of a coordinator node and several capsules moving along the GI tract.
- The path-loss of the human body varies based on different electrical properties of the body tissue and different frequencies [43]. The UHF frequency (and above) will cause severe absorption and large path-loss, while low frequency radio can penetrate the body tissue relatively easier.
- Because the capsules are of a small size around 26×11 mm (length $\times$ diameter), the power and resources for processing on the capsule are very limited.
- The coordinator node is typically outside the human body without size limitation and the batteries are easily replaced, hence the power source for the coordinator node can be considered to be unlimited.
- Many sensors could be integrated into capsules to monitor vital body signs such as temperature, blood pressure, electrocardiography (ECG), images of the GI tract. These sensors may have disparate sampling rate and sample data size. For example, the pressure and temperature sampled data may be smaller in size and lower in sampling rate than the real time image data.

- Unlike most WSN, multiple capsule networks operate only within the area of the body. This makes the capsule devices easily reachable from the coordinator.
- BS can know the number of the capsule devices in the networks. This is reasonable in the human body health care applications.

Based on all these unique attributes of multiple capsule networks, a TDMA based energy efficient MAC protocol is proposed. The asymmetric architecture, TDMA frame format, routing algorithm, hardware experiments are discussed in details.

4.2 Qualnet Simulator

Qualnet is a commercial network simulator produced by Scalable Network Technologies, Inc. [90] (Fig. 4.2). It is high-speed, ultra high-fidelity modeling and simulation software for designing and developing early-stage wireless and mixed-platform network and device performance under controlled conditions. Qualnet has the following advantages:

- an extensive set of pre-built models, protocols and algorithms,
- a good level of acceptance from the scientific community,
- an excellent scalability,
- a rather good, highly modular, software design,
- a satisfactory level of usability, modifiability and expandability,

- advanced graphical and mathematical tools for experiment building, monitoring and post-processing,
- good documentation,
- possibility of parallel and/or distributed implementations,
- possibility to specify a realistic 3D model of the environment.

Fig. 4.2 Qualnet simulator graphic user interface

Qualnet has a very friendly GUI interface. In the scenario, the user defines nodes with from PHY to APP protocols and data transmission application. A configuration file is then generated which is used as a input of the simulator. The statistic file is the output giving statistic data for each protocol in the stack. A comparison of Qualnet, NS2, and

OPNET is given in Table 4.1.

Table 4.1 Comparison of Qualnet, NS2, and OPNET

	Qualnet	NS2	OPNET
License	Commercial	Free	Commercial
Visualization	GUI/file	File	GUI
Documentation	Very good	Bad	Good
Easy to use	Yes	Yes	No
Code structure	Good	Not good	

4.2.1 Discrete-event Simulation

Qualnet is a discrete-event simulator. In discrete-event simulation, a system is modelled as it evolves over time by a representation in which the system state changes instantaneously when an *event* occurs, where an event is defined as an instantaneous occurrence that causes the system to change its state or to perform a specific action. Examples of events are: arrival of a packet, a periodic alarm informing a routing protocol to send out routing update to neighbours, etc. Examples of actions to take when an event occurs are: sending a packet to an adjacent layer, updating state variables, starting or restarting a timer, etc.

In QualNet, the data structure used to represent an event is called a message. A message holds information about the event such as the type of event, and the associated data. In the context of QualNet, the terms event and message are often used interchangeably. There are two types of events in QualNet: packet events and timer events. Packet events are used to simulate exchange of data packets between layers or between nodes. Packet events are also used for modeling communication between different entities at the same layer. Timer events are used to simulate time-outs and are internal to a protocol.

In discrete-event simulation, the simulator maintains an *event queue*. Associated with each event is its *event time*, i.e., the time at which the event is set to occur. Events in the event queue are sorted by the event time. The simulator also maintains a *simulation clock* which is used to simulate time. The simulation clock is advanced in discrete steps, as explained below. The simulator operates by continually repeating the following series of steps until the end of simulation:

- The simulator removes the first event from the event queue, i.e., the event scheduled for the earliest time.
- The simulator sets the simulation clock to the event time of the event. This may result in advancing the simulation clock.
- The simulator handles the event, i.e., it executes the actions associated with the event.

4.2.2 Modeling Protocols in Qualnet

Each protocol operates at one of the layers of the stack. Protocols in Qualnet essentially operate as a finite state machine. The occurrence of an event corresponds to a transition in the finite state machine. The interface between the layers is also event based. Each protocol can either create events that make it change its own state (or perform some event handling), or create events that are processed by another protocol. To pass data to, or request a service from, an adjacent layer, a protocol creates an event for that layer. Fig. 4.3 shows the finite state machine representation of a protocol in Qualnet. At the heart of a protocol model is an *Event Dispatcher*, which consists of a *Wait For Event* state and one or more *Event Handler* states. In the *Wait For Event* state, the protocol waits for an event to occur. When an event for the protocol occurs, the protocol transitions to the *Event Handler* state corresponding to that event (e.g., when *Event 1* occurs, the protocol transitions to the *Event 1 Handler* state). In this *Event Handler* state, the protocol performs the actions corresponding to the event, and then returns to the *Wait For Event* state. Actions performed in the *Event Handler* state may include updating the protocol state, or scheduling other events, or both.

Fig. 4.3 Finite state machine structure of a protocol in Qualnet

Besides the *Event Dispatcher*, the protocol finite state machine has two other states: the *Initialization* state and the *Finalization* state. In the *Initialization* state, the protocol reads external input to configure its initial state. The protocol then transitions to the *Wait For Event* state. The transition to the *Finalization* state occurs automatically at the end of simulation. In the *Finalization* state, protocol statistics collected during the simulation are printed.

4.3 Modeling of Human Body Channel

For the human body channel, W. G. Scanlon et al. used a semi-segmented model to

investigate the radio wave propagation characteristics of an implanted source [44]. L. C. Chirwa et al. used a fully segmented model to simulate the radiation characteristics [43]. He used simulation software XFDTD from REMCOM Inc. and data of Visible Human Project sponsored by the USA National Library of Medicine to model human body based on finite-difference time-domain (FDTD) method. L. Wang et al. performed experiments in porcine carcasses for 30-40MHz and 868MHz wireless transmission schemes for ingestible capsules [46]. The attenuation of radio within human body is dependent on body tissue properties like conductivity and permittivity, and radio frequency. The higher the conductivity, the larger the attenuation is, and the higher the frequency, the larger the attenuation is.

IEEE 802.15.6 channel modelling subcommittee proposed a mathematical channel model for BAN [91]. The proposal defines seven scenarios based on different locations of the communicating nodes as shown in Table. 4.2. These scenarios are grouped into four channel model classes (Fig. 4.4). In the multi-capsule networks, implant to implant (S1) and implant to body surface (S2) are involved.

Table 4.2 List of scenarios for body area network

Scenario	Description	Frequency Band	Channel Model
S1	Implant to Implant	402-405 MHz	CM1
S2	Implant to Body Surface	402-405 MHz	CM2
S3	Implant to External	402-405 MHz	CM2
S4	Body Surface to Body	13.5, 50, 400, 600, 900	CM3

	Surface (LOS)	MHz 2.4, 3.1,-10.6 GHz	
S5	Body Surface to Body Surface (NLOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1,-10.6 GHz	CM3
S6	Body Surface to External (LOS)	900 MHz 2.4, 3.1,-10.6	CM4
S7	Body Surface to External (NLOS)	900 MHz 2.4, 3.1,-10.6	CM4

Fig. 4.4 Possible communication links for BANs. CM means channel model.

The path loss for BSNs is both distance and frequency dependant. The path loss model is described as a function based on the Friis formula in free space in Eqn. 4.1.

$$PL(d) = PL_0 + 10n \log_{10} \left(\frac{d}{d_0} \right) \quad \text{Eqn. 4.1}$$

Where PL_0 is the path loss at a reference distance d_0 , and n is the path-loss exponent.

Due to the variation in the environment of human body, path loss will be different from the mean value for a given distance. This phenomenon is called shadowing. The shadowing should be considered for both stationary and non-stationary position of body. When considering shadowing, the total path loss PL can be expressed by Eqn.

4.2

$$PL = PL(d) + S \quad \text{Eqn. 4.2}$$

where $PL(d)$ is expressed by Eqn. 4.1 and S represents the shadowing component.

According to the channel model draft, a statistical model of path loss can be described by Eqn. 4.3.

$$PL(d) = PL(d_0) + 10n \log_{10} \left(\frac{d}{d_0} \right) + S \quad \text{Eqn. 4.3}$$

Where $S \sim N(0, \sigma_s)$ and $d_0 = 50mm$

The parameters corresponding to CM1 and CM2 are expressed in the Table. 4.3 and Table 4.4.

Table 4.3 Implant to implant CM1 (Scenario S1) for 402-405 MHz

Implant to Implant	$PL(d_0)(\text{dB})$	n	$\sigma_s(\text{dB})$
Deep Tissue	35.04	6.26	8.18
Near Surface	40.94	4.99	9.05

Table 4.4 Implant to body surface CM2 (Scenario S2) for 402-405 MHz

Implant to Body Surface	$PL(d_0)(\text{dB})$	n	$\sigma_s(\text{dB})$
Deep Tissue	47.14	4.26	7.85
Near Surface	49.81	4.22	6.81

4.4 Multi-hop Communications through Human Body

Multi-hop communication is widely used in WSNs. Short distance radio transmission relay is instead of a long distance radio transmission. The transmit power is reduced significantly. The multi-hop communication is no doubt an interesting research topic which may be used for multi-capsule communication. Multi-hop wireless communications through the air and underwater have been well studied, however, to the author's best knowledge, multi-hop communications of ingested devices has not been investigated.

The multi-hop communication and single hop communication are compared in terms of energy consumption. In Eqn.4.4, E_{single} is represented as the energy consumed by the capsule node which transmits the data directly to the coordinator node. It is equal

to the summation of E_c and $E_{t_{single}}$. E_c represents the energy consumed by the circuitry (i.e. circuitry power) and $E_{t_{single}}$ is the transmit energy. In Eqn. 4.5, E_{ij} represents the total energy consumed by node i which transmits data to node j . It is equal to the summation of E_c and $E_{t_{ij}}$. $E_{t_{ij}}$ is the transmit energy for sensor node i to transmit data to sensor node j . $\sum_n E_{ij}$ is the total transmit energy consumption for multi-hop communication. The multi-hop communication can save energy only if $\sum_n E_{ij}$ is smaller than E_{single} (Eqn. 4.6) (Eqn. 4.7).

$$E_{single} = E_c + E_{t_{single}} \quad \text{Eqn. 4.4}$$

$$E_{ij} = E_c + E_{t_{ij}} \quad \text{Eqn. 4.5}$$

$$\sum_n E_{ij} \leq E_{single} \quad \text{Eqn. 4.6}$$

$$E_c + E_{t_{single}} \geq \sum_n (E_c + E_{t_{ij}}) = n \times E_c + \sum_n E_{t_{ij}} \quad \text{Eqn. 4.7}$$

To evaluate the energy consumption for multi-hop communications through the human body, a topology of a straight line within the range of 40cm is used for this simulation (Fig. 4.5). 1 to 8 capsules and 1 base station are uniformly distributed on the line.

Fig. 4.5 Topology for wireless nodes in the simulation

The Constant Bitrate (CBR) application is from the first capsule from left hand side to the base station. For the items sent from capsule to base station, this thesis refers to

the commercial wireless capsule endoscopy from Given Imaging, 2 frames/second, 256×256 pixels. Here assume the compression ratio is 12.8. Three colors, red, green and blue are used. According to Eqn. 4.8 each frame is 15k bytes. Each frame is divided into 10 packets, so the packet size is equal to 1536 bytes. CBR packet interval is 0.05 second.

$$256 \times 256 \times 3 \div 12.8 = 15\text{k bytes} \quad \text{Eqn. 4.8}$$

GENERIC energy model is used in Qualnet simulator. Transmission signal power consumption (Pt) is adaptive and calculated as shown in Eqn. 4.9. PL is path loss value between the transmitter and receiver. Sensitivity refers to current available WCE as -84 dBm. Power consumption in transmit mode (Pont) is mainly composed of transmit circuitry power consumption (Pct) and Pt. Power consumption in receive mode (Ponr) is mainly composed of receive circuitry power consumption (Pcr) [90]. These two power consumption values are given in Eqn. 4.10 and Eqn. 4.11,

$$P_t = PL + \text{Sensitivity} \quad \text{Eqn. 4.9}$$

$$P_{ont} = (1 + \alpha) \times P_t + P_{ct} \quad \text{Eqn. 4.10}$$

$$P_{onr} = P_{cr} \quad \text{Eqn. 4.11}$$

where α is power amplifier inefficiency factor expressed in Eqn. 4.12.

$$\alpha = \frac{\beta}{\mu} - 1 \quad \text{Eqn. 4.12}$$

μ is the drain efficiency of the RF power amplifier and β is the Peak to Average Radio (PAR). β is dependant on the modulation scheme and the associated constellation size in Eqn. 4.13. This thesis assumes 4FSK is used (used by Given Imaging capsule), therefore β is 1. For μ , different classes of amplifiers have different values of μ . This thesis adopts μ from 0.35 to 0.75 (α from 0.33 to 1.86), which covers most of the range for both linear and non-linear amplifiers.

$$\beta = \frac{3 \times (\sqrt{M} - 1)}{\sqrt{M} + 1} \quad \text{Eqn. 4.13}$$

Transmit and receive circuitry power consumptions are becoming smaller and smaller as the new technologies come out. The commercial medical implantable RF transceiver ZL70102 has a TX/RX circuitry power of 5 mW (5 mA $\times$ 3V=15 mW). Sungho et al. presented a 1.5 mW CMOS BFSK transceiver in the MICS band [92]. A 350 μ W MSK transmitter and 400 μ W OOK receiver for medical implant communications are proposed by J. L. Bohorquez et al [93]. J. Pandey et al. proposed a 90 μ W MICS/ISM band transmitter [94]. F. Goodarzy introduced a new modulation scheme and the receiver obtained a 10 μ W power consumption [95]. This thesis evaluates the Tx/Rx circuitry power from 10 μ W to 15 mW.

TDMA is used as MAC protocol. For multi-hop communication, within each time slot, only sender and next hop receiver wake up. Once the transmission finishes, they go to sleep. The rest of nodes enter the sleep mode to save energy within that time slot. The

simulation assumes the process time is 0. The parameters used in Qualnet are listed in Table 4.5.

Table 4.5 Parameters used in simulation

Parameters	Value	Parameters	Value
Area	straight line of 40cm	Inefficiency factor α	1
Number of capsules	1-5	Channel frequency	405MHz
Path loss model	IEEE802.15.6 channel model	Items to send	1000
Radio type	ABSTRACT	Packet size	1536 bytes
Transmission power (dBm)	adaptive	CBR packet interval	0.05s
Energy model	GENERIC	Simulation time	30s
MAC protocol	TDMA	Transmit/receive circuitry power	from 10uW to 15mW

Because the base station is normally a data recorder attached outside the human body and the battery is easily added without strict size constraint, the energy consumption of the base station is not considered. The value of total energy consumption is the summation of the energy consumed by all the capsules for both transmit mode and receive mode.

Fig. 4.6 gives out the total energy consumption for the circuitry power consumption from 100 μ W to 15 mW. All the simulation achieves a packet delivery of 1. It can be seen from the figure that if the circuitry power is bigger than around 3 mW, single

hop wireless communication consumes less energy consumption than multi-hop communication. When the circuitry power drops below 3 mW to 100 μ W level, it can be seen that multi-hop wireless communication through human body can save power compared with one-hop communication. The lower the circuitry power is, the more meaningful the multi-hop communication is used. Given the advancement of electronic technologies, multi-hop communications through human body will become more and more meaningful.

In Fig. 4.6(b), take the curve of 1 mW circuitry power for example. The total energy consumption of 1 capsule is bigger than that of 2 capsules is because the transmit power of 1 hop communication is too large, while the transmit power of 2 hop communication is relatively small. The change of the transmit power is larger than the increase of circuitry power. The total energy consumption of 2 capsules is bigger than that of 3 capsules is because transmit powers for 2 and 3 hops are already small. The decrease of transmit power from 2-hop to 3-hop is smaller than the increase of circuitry power due to one more hop. The minimum energy consumption shifts from 2 hops to 3 hops, 4 hops when the circuitry power becomes smaller. This is because when circuitry power becomes smaller, the energy consumption of the circuit occupies less in the total energy consumption. Transmit power is dominant at this time. Multi-hop communication can reduce the transmit power significantly. Therefore, more hops achieve less energy consumption.

(a)

(b)

Fig. 4.6 Total energy consumption for different circuitry power consumption

To calculate the power efficiency, the total energy of each bit is simulated. Fig. 4.7 shows an example of energy/bit for different numbers of capsules given the circuitry power is 100 μ W. It shows that 3 hop communication achieves lowest energy/bit value when the circuitry power is equal to 100 μ W.

Fig. 4.7 Energy/bit based on different number of capsules at a circuitry power of 100 μ W

Fig 4.8 evaluates the feasibility of multi-hop communication given different α value when circuitry power is equal to 15 mW, 3 mW and 100 μ W. From Fig. 4.8 it can be seen that α gives a little influence when multi-hop (2 hop-5 hop) communication is adopted. This is because that the multi-hop communication leads to a small transmit power. Compared with the circuitry power, the transmit power contributes less to the total energy consumption. The variation of α gives little influence.

It can also be seen that for the available chipsets such as ZL70102 which has a circuitry power of 15 mW, multi-hop communication has no advantage for energy saving. When the circuitry power reduces to 3 mW, two-hop communication can achieve almost same performance in terms of energy consumption. When the circuitry

power reaches 100 μW , multi-hop communication gives much better performance than single hop communication for in-vivo communication.

(a)

(b)

(c)

Fig. 4.8 Evaluation of multi-hop communication given different α value when circuitry power is equal to 15 mW, 3 mW and 100 μ W.

Fig. 4.9 gives the latency performance for different number of capsules. It can be seen that when the network capacity increases, the latency becomes larger. This is due to the multi-hop communication. The number of hops increases for lower energy consumption, but sacrifices the latency performance.

Fig. 4.9 Latency performance for different number of capsules

As discussed above, a potential use of multi-hop network for in-vivo multiple capsule networks is expected for low circuitry power consumptions (<3 mW) in the future. Although multi-hop communications can reduce energy consumption, the latency will undoubtedly increase when the number of capsules increases. The protocol designer should balance the tradeoff between power consumption and latency to meet the requirements of the network design.

4.5 Mobility Scenario Simulation for Multi-Capsule

Communications

This section describes the mobility scenarios of multiple capsules moving along GI tract. The purpose is to test the mobile situation of the capsule networks. Two cases of mobility pattern are examined. The energy consumption for single hop and multi-hop communication are given out.

The mobility setting in Qualnet uses the mobility file which is defined by user as following format:

<node ID> <simulation-time> <position> <orientation>

Below is an example code of node 2 mobility file as shown in Fig. 4.10.

2 0 (0.19, 0.38, 0) 0 0

2 5 (0.19, 0.30, 0) 0 0

2 10 (0.27, 0.34, 0) 0 0

2 15 (0.32, 0.27, 0) 0 0

2 20 (0.29, 0.22, 0) 0 0

2 25 (0.22, 0.22, 0) 0 0

2 30 (0.18, 0.25, 0) 0 0

Fig. 4.10 The mobility pattern of multi-capsule communications

In scenario case 1, the mobility pattern is shown in Fig. 4.10. Four capsules move along the GI tract in 7 steps. Every 5 seconds, each capsule moves one step forward. The CBR data is sent from node 2 (capsule) to base station. Item size is 1536 bytes,

and interval is 0.05 seconds. TDMA is used as the MAC protocol and Bellman Ford is used as the routing protocol. The minimum transmit powers for single hop and multi-hop communications are 2 dBm and -4 dBm which obtain the packet delivery ratio of 1. The simulation time is 35 seconds. Simulation parameters are shown in Table 4.6.

Table 4.6 Parameters used in simulation

Parameters	Value	Parameters	Value
Area	0.5m×0.5m	Transmit/receive circuitry power	10uW, 100uW, 1mW, 10mW
Number of nodes	5	MAC protocol	TDMA
Channel frequency	405MHz	Routing protocol	Bellman ford
Pathloss model	802.15.6 channel model	Mobility model	File
Radio type	Abstract	Items to send	1000
Transmission power (dBm)	2, -4	Packet size	1536 bytes
Energy model	GENERIC	CBR packet interval	0.05s
Inefficiency factor α	1	Simulation time	35s

The simulation result is as follow in Fig. 4.11 and Fig. 4.12. In Fig. 4.11, the total energy consumption increases with the increasing of circuitry power consumption. When circuitry power is equal to 10 uW, 100 uW and 1 mW, multi-hop communication achieves lower energy consumption than single hop communication. When the circuitry power is equal to 10 mW, single hop communication has lower

energy consumption. Fig. 4.12 shows the relationship between Energy/bit value and circuitry power consumption.

Fig. 4.11 Energy consumption of mobile capsules within GI tract

Fig. 4.12 Energy/bit for multiple capsule networks

In case 2, another mobility pattern is modeled as Fig. 4.13. It is much closer to the real small intestine. Many curves of different directions are modeled for the small intestine. Fig. 4.12b is calculated by Matlab. 100 points are chosen as the waypoint of the mobility pattern. Granularity is set to be 6cm.

(a)

(b)

Fig. 4.13 Small intestine mobility pattern

The network area is within a cube of 25cm×25cm×15cm. Four capsules and a BS are in the scenario. 405MHz is chosen as the radio frequency. Path loss model adopts IEEE802.15.6 channel model. 10uW, 100uW, 1mW, and 10mW are used in the simulation as the transmit/receive circuitry power. The minimum transmit power is 1 dBm for single hop communication and -5 dBm for multi-hop communication to obtain a packet delivery ratio of 1. The parameters are shown in Table 4.13.

Table 4.7 Parameters used in simulation

Parameters	Value	Parameters	Value
Area	25cm×25cm×15cm	Transmit/receive circuitry power	10uW, 100uW, 1mW, 10mW
Number of nodes	5	MAC protocol	TDMA
Channel frequency	405MHz	Routing protocol	Bellman Ford
Path loss model	802.15.6	Mobility pattern	Small intestine model
Radio type	Abstract	Items to send	12000
Transmission power (dBm)	1, -5	Packet size	1536 bytes
Energy model	Generic	CBR packet interval	0.05s
Inefficiency factor α	1	Simulation time	490s

Simulation results are shown in Fig. 4.14 and Fig. 4.15. From Fig. 4.14, we can see that the multi-hop communication achieves lower energy consumption than single hop communication when circuitry power is equal to 10 μ W, 100 μ W and 1 mW, but has larger energy consumption when the circuitry power is equal to 10 mW. When circuitry power consumption increases, the total energy consumption increases correspondingly. When the circuitry power is equal to some value between 1 mW and 10 mW, single hop and multi-hop communications achieve the same energy consumption. Fig. 4.15 shows the energy/bit for both multi-hop and single hop communication. This value is almost the same as in Case 1, which demonstrates that when other conditions are the same, mobility pattern influences the energy consumption for one bit transmission less.

Fig. 4.14 Energy consumption of mobile capsules within GI tract

Fig. 4.15 Energy/bit for multi-capsule networks

This part tests two mobile scenarios for energy consumption analysis. In the two mobile cases, the multi-hop communication gives a good performance when the circuitry power is lower, while not energy efficient if the circuitry power is high. This matches previous simulation results.

4.6 MAC Protocol Design for Multiple Capsule Networks

Based on the review of MAC protocols of WSNs and BSNs as well as the analysis of multi-hop communication through the human body, this part proposes a novel MAC protocol for multiple capsule networks. For this special multi-capsule networks, there are some unique properties which are listed as below:

1. Real time data. No tolerance of latency, because the doctors need to do the real time treatment.
2. High data rate. The video will be transmitted outside for doctor to see the situation of GI tract.
3. Mobility. Capsules move along GI tract.
4. Central coordinator (base station) is possible. The area is only inside human body.
5. Energy constraints. Capsules have very little power, while the central coordinator has sufficient power.
6. Number of capsules is not large. The amount is known by the central coordinator (data recorder).
7. Because it is for medical diagnostic and treatment, stability and performance is far more important than the cost.
8. Pathloss is severe.

According to the properties of multi-capsule scenario, a kind of centralized TDMA MAC protocol is proposed, because:

1. For the sensing data, such as image, temperature, the data rate is a fixed value, not burst data, so contention-based protocol is not a good solution
2. The delay is a constant value which is good for real time application.
3. TDMA can avoid packet loss due to collision although overhead may increase.
4. The coordinator can schedule the transmission not only based on the path loss but also based on the remaining energy of every capsule.

5. The routing is calculated by coordinator, not by capsules. This can reduce power consumption at capsule side.
6. The logic is clear and the algorithm is easily implemented.

The idea of this centralized TDMA MAC protocol is:

1. Base station synchronizes all the capsules.
2. Capsules collect neighboring information and send to base station.
3. According to the neighboring information, base station calculates the best route which has the smallest path loss.
4. Base station sends the schedule back to every capsule.
5. After that, all nodes will follow this schedule to transmit data.
6. The routing update is done periodically.

The details of network architecture, TDMA frame format, and adaptive power control will be discussed below.

4.6.1 Asymmetric Topology

A novel uplink, downlink asymmetric topology is proposed, which is suitable for the multiple capsule scenario. For most communication networks, uplink and downlink follow the same route. In WLAN and mobile telecommunication network, every terminal communicates directly with the base station (Fig. 4.16), forming a

centralized topology. Base station manages the whole network. However, this topology is not suitable for a multiple capsule network because body tissue absorbs the electromagnetic waves significantly, and then there could be significant energy loss if each capsule communicates with the base station directly.

Fig. 4.16 Centralized topology

The multiple capsule networks have some similar properties to typical wireless sensor networks [96](Fig. 4.17), like the limited power resources and the need to operate in face of mobility. As discussed previously, a multi-hop routing can save significant amount of energy. A possible solution for a robust multi-capsule network is for the capsules to form a multi-hop network in which capsules relay data packets for each other. The route with the smallest energy loss of the whole communications is chosen.

Fig. 4.17 Distributed topology

However, for this particular multi-capsule scenario, the data recorder (base station) and capsules have different power constraints. Data recorder almost has sufficient power reserves and a transmission range enabling it to reach capsules, but capsules have very limited power, which is the most important part for the protocol design.

Fig. 4.18 Asymmetric link topology

Therefore, a novel uplink, downlink asymmetric topology is proposed. It is a mixture of the centralized architecture and the distributed architecture (Fig. 4.18). For downlink data transmissions, because the coordinator node is outside the human body

with no strict constrain in size, the radio of the coordinator node could easily cover all the capsule devices. Based on this, single hop communication is adopted. The coordinator node is assumed to have unlimited energy and thus, its energy consumption is not considered. The total energy consumed by the capsules to receive data from the coordinator node directly can be calculated as the receiving energy consumption of the capsule device, E_r . If the coordinator node sends data by a multi-hop way through node group K , then the total energy consumption is equal to $E_r + \sum_K (E_{r_i} + E_{t_i})$. E_{r_i} and E_{t_i} are the receiving energy consumption and the transmitting energy consumption of node i ($i \in K$), respectively. Obviously the energy consumption of the downlink multi-hop communication is larger than the energy consumption of direct transmission.

For uplink data transmission, because the capsule devices have very limited power and the batteries are not easily replaced, and the path-loss inside the human body is large, multi-hop communication is adopted. Previous result shows that it uses less energy consumption than single hop communication.

4.6.2 TDMA Frame Format Design

In multiple capsule networks, because the wireless coverage of the coordinator node can reach all the capsule devices, network synchronization can be easily achieved. Therefore a TDMA based MAC protocol is proposed. The TDMA scheme can avoid collision, idle listening, and overhearing. It can also maximize the bandwidth

utilization.

Fig. 4.19 TDMA frame format

In the proposed MAC protocol, time slots are assigned by the coordinator node. Fig. 4.19 shows the frame format of the TDMA frame. It is composed of a number of control slots and data slots. Control slots include synchronization slot, broadcast slot, power detection slots, neighboring information upload slots, and schedule assignment slots. Synchronization information is broadcasted by the coordinator node in the beginning of the frame. All sensors must keep listening in the first time slot in order to be synchronized with the whole network. In the second time slot the coordinator broadcasts the control section schedules for all the capsules. It gives the starting slot for power detection, neighboring information uploading, and schedule assignment, respectively. All the capsules receive this broadcast information and use its own identification (ID) as the shift to calculate their own transmit time slot for power detection, neighboring information uploading, and schedule assignment. In the power detection section, each sensor broadcasts its own information including sensor ID and transmit power in its own time slot. During the rest of the time, it listens for the power detection information of other nodes. In this section, the transmit power must be large enough to ensure that all the other capsules can hear and receive this neighboring

information. In the upload section, the capsules send the collected information and its time slot request to the coordinator node. They go into sleep mode when other nodes send upload data to the coordinator node in order to save energy. After coordinator node receives all these neighboring information and time slot request, it begins to calculate routing and slot schedule pattern. The time slot assignment is completely flexible. If a capsule has a lot of data to send, then it would be assigned more data slots. If a capsule has no data to send, then it would not be assigned data slots. In the schedule assignment section, the coordinator node sends the schedules to the capsules. The capsules only receive in their own slots and during the rest of the time in this section they are in the sleep mode. The schedules includes information about the transmit time slot, receive time slot and the transmit power for the specific capsule in the following data slot section. In the data slot section, the capsule devices follow the received schedules to complete the communications. The whole process repeats in the next TDMA frame. Fig. 4.21 shows an example of TDMA frame for four capsules in the network. The packet structures of the control data are given in Fig. 4.22.

Fig. 4.20 TDMA schedules

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14	16		51				69
1	ctx	ctx	rx	rx	rx	rx	rx	rx	rx	rx			ctx	ctx	ctx	ctx						
2	rx	rx	ctx	rx	rx	rx	ctx	sleep	sleep	sleep			rx	sleep	sleep	sleep						
3	rx	rx	rx	ctx	rx	rx	sleep	ctx	sleep	sleep			sleep	rx	sleep	sleep						
4	rx	rx	rx	rx	ctx	rx	sleep	sleep	ctx	sleep			sleep	sleep	rx	sleep						
5	rx	rx	rx	rx	rx	ctx	sleep	sleep	sleep	ctx			sleep	sleep	sleep	rx						
	sync		power detection				upload						schedule assignment					data slots				

Fig. 4.21 Frame format for a four sensor BSN

Fig. 4.22 Data packet structures

Fig. 4.23 Changeable frame format

Because the capsules move very slowly in the GI tract, there is no need to conduct the power detection and update the route for every frame format. A changeable frame format is thus proposed. Besides the frame format as shown in Fig. 4.23(a), a simplified format is given in Fig. 4.23(b). This frame format omits the sections of power detection, upload and schedule assignments. It is composed of a synchroninaztion slot and pure data slots for the rest. Take a N frame update as an

example. If the power detection updates is performed in every frame, then the total energy required is equal to $N \times (E_c + E_s)$. E_c is the energy consumption for the control section and E_s is the energy consumption for the sensing data. If the power detection updates is performed once every N frame, then the total energy consumption becomes $N \times E_s + E_c$. It is obvious that the N frame update scheme consumes less energy.

Fig. 4.24 shows the simulation results for the fixed frame format and the changeable frame format. All the simulations obtain 100% packet delivery ratio. It can be seen that the energy consumption for 1 frame /update is always larger than that of 3, 5, 7 and 9 frames/update which proves that the changeable frame format can effectively save energy. The longer the update is done, the less the energy is consumed. However, the frequency of the power detection cannot be reduced indefinitely. It is related to the moving speed of the capsules. The optimization of the power detection frequency will be discussed later.

Fig. 4.24 Energy consumption for fixed and changeable frame format

From the figure it can also be noticed that the energy consumption for 3 capsules is lowest. This is because 3-hop achieves the lowest energy consumption. If there are 2 capsules, then the transmit power is relatively larger which results in higher energy consumption. If there are 4 or 5 capsules, the route and transmit power do not change, but additional control overhead is added due to the fifth capsules. That is why that the energy consumption for 4 or 5 capsules is larger than that of 3 capsules. This will be explained later.

4.6.3 Routing and Adaptive Power Control

All the neighbor information are collected by the capsule devices and sent to the BS with time slot request. BS calculates the routing, transmit power and the slot assignment for each capsule. From the neighboring information, the pathloss PL of

any two sensors can be calculated according to Eqn. 4.14 using the transmit power and received signal strength indication (RSSI). P_t is the transmit power from node i to node j . RSSI is the receiving power of node j . The minimum power consumption, $P_{t_{ij}}(\text{dB})$, of any two sensor devices can be calculated according to Eqn. 4.15 and Eqn. 4.16. BS initializes the next hop array and total power array. The initial next hop of any node is BS. The total power of node i is the power consumption for data transmission from node i to BS calculated as Eqn. 4.17. $\sum_{\text{route}} P_{t_{ij}}$ is the summation of transmit power in the route. $\sum_{\text{route}} P_{r_{ij}}$ is the summation of receive power except the BS. Excluding the receive power consumption of BS is because BS is outside the human body with large volume, so it is assumed BS has unlimited power. For each round calculation, if $\text{TotalPower}(i \rightarrow j \rightarrow \text{BS}) < \text{TotalPower}(i)$, then the next hop of node i becomes node j . The corresponding total power is updated. The route calculation is finished until the next hop array does not change. For the chosen route, the corresponding transmit power can be calculated according to Eqn. 4.15. Algorithm 1 shows the route calculation algorithm.

$$PL = P_t - \text{RSSI} \quad \text{Eqn. 4.14}$$

$$P_{t_{ij}}(\text{dB}) = \text{Sensitivity} + PL_{ij} + P_{\text{guard}}(\text{dB}) \quad \text{Eqn. 4.15}$$

$$P_{t_{ij}} = 10^{\frac{P_{t_{ij}}(\text{dB})}{10}} \quad \text{Eqn. 4.16}$$

$$\text{TotalPower}(i) = \sum_{\text{route}} P_{t_{ij}} + \sum_{\text{route}} P_{r_{ij}} \quad \text{Eqn. 4.17}$$

Algorithm 1 Route calculation

V: set of all the medical nodes in the networks

```

SET Nexthop(node i) = BS

SET TotalPower(node i) = TotalPower(i->BS)

WHILE NexthopArray changed do

    WHILE  $i \in V$  do

        WHILE  $j \in V, j \neq i$  do

            if TotalPower(i->j->BS) < TotalPower(i) Then

                Nexthop(i)=j

                TotalPower(i)= TotalPower(i->j->BS)

            End if

        End While

    End While

    check if NexthopArray is changed

End While

```

4.6.4 Implementation of the TDMA Protocol in Qualnet

Implementing TDMA protocol in Qualnet mainly uses the timer. Set the timer with an expired duration of one slot. Every time the timer expired, the system will check the current status, TX, RX, or idle. If it is idle, then ask physical layer to stop listening the channel; if the current status is RX, then ask the physical layer to start listening the channel; if the status is TX, then dequeue packet from network queue, add the header, and ask physical layer to send them out. After all these procedures, update the timer and restart it. Fig. 4.25 shows the flow chart of TDMA protocol.

Fig. 4.25 Flow chart of TDMA protocol

Below are the functions for TDMA MAC protocol

```
1. void MacTdmaInit( Node *node, int interfaceIndex, const NodeInput*
    nodeInput,    const int subnetListIndex, const int slotsperframe);
```

// Initialization function for TDMA protocol of MAC layer.

// Parameters:

// node: node being initialized.

// nodeInput: structure containing contents of input file

```
2. void MacTdmaLayer( Node *node, int interfaceIndex, Message *msg);
```

// Models the behaviour of the MAC layer with the TDMA protocol on receiving the message enclosed in msgHdr.

// Parameters:

// node: node which received the message

// msgHdr: message received by the layer

```
3. void MacTdmaFinalize(Node *node, int interfaceIndex);
```

// Called at the end of simulation to collect the results of the simulation of TDMA protocol of the MAC Layer.

// Parameter:

// node: node for which results are to be collected.

```
4. void MacTdmaNetworkLayerHasPacketToSend(Node *node, MacDataTdma
    *tdma);
```

```
// To tell TDMA that the network layer has a packet to send.
```

```
5. void MacTdmaReceivePacketFromPhy(Node* node, MacDataTdma* tdma,
    Message* msg);
```

```
// called by phy layer to receive packet from phy layer
```

```
6. void MacTdmaReceivePhyStatusChangeNotification( Node* node,
    MacDataTdma* tdma, PhyStatusType oldPhyStatus, PhyStatusType
    newPhyStatus);
```

```
// called by phy layer to receive status change notification from phy layer
```

4.6.5 Simulation Results

The multiple capsule networks inside the small intestine were simulated using Qualnet 5.0. The energy consumption, latency and duty cycle of the proposed MAC protocol were simulated and compared with IEEE802.15.6 draft. The results showed that the proposed MAC protocol outperforms 802.15.6 in terms of energy consumption.

The mobility pattern is randomly generated. The small intestine is over 6 meters in length [27] and the nodal speed in the digestive tract is around 0.2mm/s [97]. The

assumptions in Table 4.8 are made to randomly generate the mobility patterns of the small intestine. According to the small intestine model, the mobility pattern is modeled as multi segment line around 6.3 meters inside a cube of 25cm×15cm×25cm. Each segment line follows normal distribution with the mean length of 7.8cm and the standard deviation of 3.1229cm. The angle of each segment line to the coordinate, α and β , follows uniform distribution with the minimum value of 0° and maximum value of 360° . The mobility pattern starts at (7, 11.3, 25) and ends at (0, 0.231, 4). The algorithm for generating the random mobility pattern is shown as Algorithm 2.

Table 4.8 Assumptions for random mobility pattern generation

maximum angle	360	mean of distance	7.361
minimum angle	0	standard deviation	3.1229
Length of small intestine	~630cm	border	25*15*25
starting point	(7,11.3,25)	destination point	(0,0.231,4)

Algorithm 2 Random mobility pattern generation

V: the border of wireless networks

SET Starting point = (7,11.3,25)

SET destination point = (0,0.231,4)

SET sumLength = 0

SET Mean of the length = 7.361

SET Standard deviation of the length = 3.1229

WHILE sumLength < TotalLength **do**

 randomly generate a length value

randomly generate the angle value, α , β

 tmpx(i)=tmpx(i-1)+tmpLength*cos(β)*cos(α);

 tmpy(i)=tmpy(i-1)+tmpLength*cos(β)*sin(α);

 tmpz(i)=tmpz(i-1)+tmpLength*cos(β);

IF tmp(i) $\in V$ **Then**

 record this point

 sumLength=sumLength+tmpLength;

 i=i+1;

ELSE

 Re randomly generate a point

End if

End While

Last point is the Pdestination;

IEEE 802.15.6 is used as reference to compare with proposed TDMA MAC protocol.

The capsule devices and coordinator node communicate in a point-to-point mode. In

the simulation no acknowledgement is adopted, which is a fair comparison with

proposed protocol. The small slots are equally assigned to capsule devices in advance.

The transmit power of 802.15.6 is set to 2dBm which is the minimum transmit power

required to ensure a delivery ratio of 1.

Fig. 4.26 Packet delivery ratio for 802.15.6

For the proposed TDMA protocol simulation, 405MHz is used as the wireless communication frequency. The payload size for synchronization, power detection and scheduling assignment is defined as 10 bytes and the payload size for broadcasting and neighboring information uploading is defined as $10 \times N$, where N is the number of the sensor devices. The total energy consumption is calculated as the summation of the energy consumption of the transmit, receive and idle states for all the capsule nodes. In our model, the power consumption in transmit mode is composed of the transmit circuitry power consumption and transmission signal power consumption, and the power consumption in receive/idle mode is equal to the receive circuitry power consumption. The routing update performs in every frame. The simulation parameters used in Qualnet are listed in Table 4.9.

$$E_{total} = \sum_{sensors} (E_{tx} + E_{rx} + E_{idle}) \quad \text{Eqn. 4.18}$$

Table 4.9 Parameters used in simulation

Parameters	Value	Parameters	Value
Area	0.4m×0.4m	Transmit/receive circuitry power	100uW
Number of capsules	2-6	MAC protocol	TDMA, 802.15.6
Channel frequency	405MHz	Mobility pattern	Random
Path loss model	802.15.6	Items to send	20000
Radio type	ABSTRACT	Packet size	512 bytes - 3k
Transmission power (dBm)	adaptive	CBR packet interval	0.2s - 1 s
Energy model	GENERIC	Simulation time	20000s
Inefficiency factor α	1	Routing update freq	1 frame/update

The energy consumption for proposed TDMA based MAC protocol and 802.15.6 draft is compared for different circuitry power and different α in Fig. 4.27, Fig. 4.28 and Fig 4.29. All the simulations obtain the packet delivery ratio of 1. In Fig .4.27, it can be seen that when circuitry power is equal to 100 μ W, the energy consumption of the proposed TDMA is smaller than 802.15.6 for α is equal to 0.33, 0.82 and 1.86 (0.33-0.86 covers the range for both linear and non-linear amplifier). For Fig. 4.27, the 3-capsule network using proposed TDMA achieves lowest energy consumption. 2-capsule network has a higher energy consumption is because that capsules use large transmit power to send data due to the longer distance between sensor nodes. 4-6 capsule networks have a larger energy consumption compared to 3-capsule network is because that at the circuitry power of 100 μ W, 3-hop achieves lowest energy

consumption. So even more capsules are in the network and logically data can be transmitted by more than 3 hops, routing protocols still choose 3-hop route. The same route means the same transmit power. Since 4-6 capsules also participate the control section of power detection, information uploading and schedule assignment, extra energy consumption is consumed. The more capsule exist in the network, the more energy is consumed. The energy consumption for 4-6 capsules increases linearly.

(a) Energy consumption when circuitry power is 100 μ W and alpha is 0.33

(b) Energy consumption when circuitry power is 100 μ W and alpha is 0.82

(c) Energy consumption when circuitry power is 100uW and alpha is 1.86

Fig. 4.27 Energy consumption vs. number of capsules when circuitry power is 100uW

Fig. 4.28 shows the energy consumption of different number of capsules when circuitry power is 1 mW and α is equal to 0.33, 0.82 and 1.86. It can be seen that the energy consumptions of 802.15.6 and proposed TDMA are almost the same. 2-hop communication achieves lower energy consumption than 802.15.6. The energy consumption of proposed TDMA increases linearly when the number of capsules increases. This means that only control overhead increases. When the circuitry power is equal to 0.33, 2-capsule network saves energy consumption while 3-capsule network consumes more energy consumption than 802.15.6. When the circuitry power is equal to 0.82, 3-capsule networks saves energy consumption compared to 802.15.6. When the circuitry power is equal to 1.86, 5-capsule networks saves energy consumption compared to 802.15.6. This is because that larger α leads to larger

energy consumption for transmitting. The energy consumption of 802.15.6 increases significantly. Due to the multi-hop communication, proposed TDMA does not lead that significant increase of energy consumption. The bigger the energy consumption for transmitting, the more meaningful multi-hop communication is.

(a) Energy consumption when circuitry power is 1mW and alpha is 0.33

(b) Energy consumption when circuitry power is 1mW and alpha is 0.82

(c) Energy consumption when circuitry power is 1mW and alpha is 1.86

Fig. 4.28 Energy consumption vs. number of capsules when circuitry power is 1 mW.

Fig. 4.29 shows the energy consumption vs. number of capsules when circuitry power is equal to 5 mW and α is equal to 0.33, 0.82 and 1.86. The energy consumption of the proposed TDMA is bigger than 802.15.6 for these three figures. This is because that the circuitry power is larger compared with transmit power. When circuitry power is equal to 5 mW, 1-hop is calculated route. The extra energy consumption of proposed TDMA compared to 802.15.6 is due to control information. In these three figures, the energy consumption of proposed TDMA also increase linearly when number of capsules increases.

(a) Energy consumption when circuitry power is 5mW and alpha is 0.33

(b) Energy consumption when circuitry power is 5mW and alpha is 0.82

(c) Energy consumption when circuitry power is 5mW and alpha is 1.86

Fig. 4.29 Energy consumption vs. number of capsules when circuitry power is 5 mW.

In summary, the proposed TDMA based MAC protocol achieves lower energy consumption than 802.15.6 when the circuitry power is 100 μ W. The main reason is multi-hop and adaptive power control. But if the transmit power is not dominant compared to circuitry power, proposed protocol would have no advantage.

Fig. 4.30 Energy consumption vs. packet size when circuitry power is 100 μ W

Fig. 4.30 shows the energy consumption vs. packet size from 0.5KB to 3KB. The same result that the proposed TDMA consumes much less energy than 802.15.6 is obtained. Fig. 4.31 gives the simulation of energy consumption vs. constant bit rate (CBR) packet interval. The proposed TDMA achieves significant performance gain for CBR packet interval from 200ms to 1s.

Fig. 4.31 Energy consumption vs. CBR packet interval when circuitry power is 100 μ W

However, for the delay performance, the proposed TDMA shows worse performance than 802.15.6. Fig. 4.32 gives the average end-to-end delay. 802.15.6 manages to consistently achieve a stable low latency for different network capacity. While for the proposed TDMA, the average end-to-end delay is very large and it increases when the network capacity becomes larger. This is due to the adaptive power control. The routing is calculated for achieving lower energy consumption. More hops can obtain lower energy consumption but cause larger delays at the same time. Another reason for the unfavorable delay performance is the TDMA frame format. In the TDMA

frame format proposed, the data slots are followed by the control data slots. This would cause delay if the data is supposed to be sent during the control data section. The assigned slots would also introduce delay. For example, data transmission may be finished before the end of the slot, but other data transmission cannot start until the next slot.

Fig. 4.32 Average end-to-end delay vs. number of capsules

Duty cycle analysis

Duty cycle is a very important concept in energy efficient MAC protocol design. It refers to the percentage of time in active status [17]. It is computed as Eqn. 4.19

$$DC = \frac{T_{\text{active}}}{T_{\text{frame}}} \times (1 + PER) \quad \text{Eqn. 4.19}$$

where T_{active} is the time duration of active status within one TDMA frame. T_{frame} is the TDMA frame duration. PER is the packet error rate.

$$T_{\text{active}} = T_{\text{data}} + T_{\text{oh}} + \frac{T_{\text{sync}}}{N_R} \quad \text{Eqn. 4.20}$$

where T_{data} is the time duration for data transmission. T_{oh} is the time duration for overhead transmission. T_{sync} is the time duration for synchronization transmission and N_R is TDMA resynchronization rate.

$$\begin{aligned}
 DC &= \frac{T_{\text{data}} + T_{\text{oh}} + \frac{T_{\text{sync}}}{N_R}}{T_{\text{frame}}} \times (1 + PER) \\
 &= \frac{N_{\text{data}} + N_{\text{oh}} + \frac{N_{\text{sync}}}{N_R}}{f_c \times T_{\text{frame}}} \times (1 + PER) \\
 &= \frac{T_{\text{frame}} \times f_s + N_{\text{oh}} + \frac{N_{\text{sync}}}{N_R}}{f_c \times T_{\text{frame}}} \times (1 + PER)
 \end{aligned} \tag{Eqn. 4.21}$$

where,

DC duty cycle

N_{data} sampling data bits within one frame time

N_{oh} overhead bits within one frame time

N_{sync} synchronization bits within one frame time

f_c communication data rate (bits per second)

f_s sampling data rate (bits per second)

Fig. 4.33 shows the duty cycle of the proposed TDMA and 802.15.6. The duty cycle of the proposed TDMA is bigger than 802.15.6 because of larger overhead and the multiple transmissions of the same data. However, since the capsule utilizing the proposed protocol will be transmitting with lower transmission strength, the overall energy consumption will still be lower than 802.15.6 as previous presented results.

Fig. 4.33 Duty cycle vs. number of nodes

Energy consumptions for different routing update frequencies are shown in Fig. 4.34.

The circuitry power is $100 \mu\text{W}$ and α is 0.82. **All the simulations obtain the packet delivery ratio of 1.** It can be seen that the energy consumption for proposed TDMA is smaller than that of 802.15.6. This is because the proposed protocol uses smaller transmit power to send the data and reduces the idle listening and overhearing. For the routing update frequency, it can be seen that the lower the update is conducted, the less the energy is consumed. When the frequency is reduced to 7 or 9 frames/update, the influence of the frequency is not too significant. The minimum energy consumption is achieved at 3-capsule network. This is explained previously that the calculated 3-hop routing obtains lowest energy consumption.

Fig. 4.34 Energy consumption vs. number of capsules

Fig. 4.35 shows the energy consumption vs. packet size from 0.5KB to 3KB. The energy consumption increases linearly when the packet size increases. The energy consumption of the proposed MAC protocol of all the update frequencies is smaller than 802.15.6. Regarding the update frequency, it can be seen that 1 frame/update consumes largest energy compared with other update frequencies. The lower frequency the update is conducted, the less the energy is consumed. If the packet size increases, the influence of routing update frequency becomes less significant.

Fig. 4.35 Energy consumption vs. packet size

Fig. 4.36 gives the simulation of energy vs. sampling rate. The proposed TDMA gives better performance than 802.15.6 for sampling rate from 200ms to 1s. It is also a linear decrease when the CBR interval becomes large.

Fig. 4.36 Energy consumption vs. CBR interval

4.6.6 Summary

This part proposed a novel TDMA based MAC protocol for multiple capsule networks. A novel asymmetric topology is used, which is better than the pure star topology or distributed topology. Sensors periodically send neighboring information to the coordinator. The coordinator calculates the routing schedule and the transmit power for each sensor device, and send them back to the sensors. The proposed protocol avoids the idle listening, overhearing problem and most of the processing work is shifted to the BS. A changeable frame format is proposed and the power detection frequency is discussed. Simulation results show the proposed TDMA protocol gives better performance than 802.15.6 in terms of energy consumption.

4.7 Discussion of Latency and Overhead Reduction of the Proposed TDMA MAC Protocol

4.7.1 Latency Analysis

For this novel capsule networks, some applications have a critical requirement of latency performance. There is a tradeoff between latency and power consumption. Star topology network achieves a very low latency performance, while it consumes relatively large energy consumption. Multi-hop network has lower power consumption than star topology network, but the latency becomes larger (Fig. 10). Minimizing the latency for a multi-hop communication becomes an issue.

Average end to end delay can be calculated as

$$\text{Average end to end delay} = \frac{\sum_{\text{all packets}} (T_{rx} - T_{tx})}{\text{Number of packets}}$$

where $T_{rx} - T_{tx}$ is the time duration from the CBR client application layer to the CBR server application layer. It is equal to

$$T_{rx} - T_{tx} = \sum_{\text{multihop}} (T_{txstack} + T_{rxstack} + T_{transmission} + T_{mac})$$

$T_{txstack}$ is the time duration for a data packet to go through the stack excluding MAC layer in the transmitter side. $T_{rxstack}$ is the time duration for a data packet to go through the stack excluding MAC layer in the receiver side. $T_{transmission}$ is the time of a data from the transmitter to a receiver. T_{mac} is the time duration consumed for a data packet through the MAC layer. From the equation, T_{mac} is the key part for reducing the average end-to-end delay.

Reducing data slot duration can reduce T_{mac} effectively. Fig. 4.37 shows the delay performance based on the data slot duration ranging from 10ms to 40ms for different network size. It can be seen that the delay decreases, when the data slot duration reduces. This is because that the decreasing of the data slot could make the assigned time slot comes earlier for the specific node. Accordingly, the whole time of $T_{rx} - T_{tx}$ becomes smaller. The delay of 2 capsules is smaller than that of more capsules is because the more capsules exist, the more time needed for the control

slots.

Fig. 4.37 Delay performance

The mini slots for control data also influence the delay performance. If a data packet from the transmitter arrives at MAC layer in the control data period, it has to wait until the control period finishes and starts to transmit in its own slot. Therefore, reducing the control data slots can reduce the total delay. Fig. 4.38 gives the delay vs. percentage of control data within one frame. It can be seen that the delay reduces when the control data occupies less within one frame. Because the control slot is already short, so the influence is not significant.

Fig. 4.38 Delay performance for mini slot optimization

As discussed above, for the multi-hop capsule networks, reducing control data and data slot duration can effectively reduce the average end to end delay therefore improve the system performance. Besides reducing the control data and data slot duration, optimizing the slot assignment algorithm can also decrease the delay. This will be discussed in the future works.

4.7.2 Overhead Reduction

TDMA based MAC protocol brings several advantages, such as no collision, very little idle listening, and no overhearing. However, it sacrifices the overhead. TDMA protocol needs to maintain synchronization with BS, exchange the node neighboring information, and receive the slot assignment. In section 4.6.2, it has been discussed that the changeable frame format can effectively reduce the energy consumption by

periodically conducting power detection instead of collecting the neighboring information for every frame. However, the interval of power detection cannot be decreased indefinitely as it is related to the moving speed of the sensor devices. As shown in Fig. 4.39, if node A wants to send a packet to node B , the transmission power Pt and the distance between the node A and node B must satisfy the relationship as in Eqn. 4.22, where M is the coefficient defined as the ratio of path-loss to distance between of any two nodes. Node A moves to the position $\vec{A} + \vec{v}_A t$ and node B moves to the position $\vec{B} + \vec{v}_B t$. The power detection is not necessary only if Eqn. 4.23 is satisfied. If the sensors move faster, Eqn. 4.23 may not be satisfied and transmission will fail. There is another scenario in which Eqn. 4.23 can be satisfied but the sensors are already nearer to each other thus Pt is set to a higher value than necessary. This will cause unnecessary energy wastage. The optimal power detection frequency can be calculated by the coordinator based on the collected neighboring information.

Fig. 4.39 Movement of capsule nodes

$$Pt - M \times |\vec{A} - \vec{B}| > \text{Sensitivity} \quad \text{Eqn. 4.22}$$

$$Pt - M \times |\vec{A} + \vec{v}_A t - \vec{B} + \vec{v}_B t| > Sensitivity$$

Eqn. 4.23

Fig. 4.40 Packet delivery ratio vs. power detection interval

Fig. 4.40 gives the packet delivery ratio for different network capacity with the moving speed of 0.2mm/s. The power detection interval can be increased, but up to some value, the packet delivery ratio would be decreased from 1. The maximum power detection interval can be obtained from figure. From the figure it can also be known that for the network with more sensor nodes, the less the power detection interval is. 5-capsule network can have a smaller power detection interval than 3-capsule network. Fig. 4.41 shows the maximum power detection interval for

different moving speed of sensors. It can be seen that when the sensor devices move faster from 0.2 mm/s to 1 mm/s, the power detection interval becomes smaller from 80 s to 10 s to successfully receive all the data. When the capsule move fast, the transmit power has to be changed also fast to reach the receiver.

Fig. 4.41 Maximum power detection interval vs. capsule moving speed

Fig. 4.42 shows that the product of maximum update interval and capsule moving speed is a constant value no matter what moving speed of capsule is. The BS can optimize the update interval value based on this relationship to reduce the overhead therefore reduce the energy consumption of the capsule nodes. From the figure it can also be known that product value is different for different network capacities. 3-capsule network has a larger value than 5-capsule network.

Fig. 4.42 Product of maximum update interval and capsule moving speed

4.8 Summary

This chapter proposes a novel topology for multi-capsule networks, which has uplink, downlink asymmetric routes to communicate bidirectionally. A TDMA MAC protocol is proposed for multi-capsule networks. It can save power by eliminating collision and idle listening. The frame format and burst format is given. Simulations of proposed TDMA and 802.15.6 are conducted based on the latest 802.15.6 channel model and randomly generated mobility pattern. The results show that the proposed TDMA protocol gives better performance than 802.15.6 in terms of energy consumption when the circuitry power is lower to certain level.

Chapter 5 Hardware Implementation of the Proposed MAC Protocol

The proposed TDMA MAC protocol is implemented using the hardware platform TI CC1110. The experiment results as well as simulation results are analyzed.

5.1 Hardware Setup

CC1110 is used for our hardware testing. The CC1110Fx/CC1111Fx is a true low-power sub 1 GHz system on chip (SoC) designed for low power wireless applications. The CC1110Fx/CC1111Fx combines the excellent performance of the state-of-the-art RF transceiver CC1101 with an industry-standard enhanced 8051 MCU, up to 32 kB of in-system programmable flash memory and up to 4 kB of RAM, and many other powerful features. The small 6x6 mm package makes it very suited for applications with size limitations. Table 5.1 gives the key features of CC1110.

Table 5.1 Key features of CC1110

Radio	Low power consumption
High sensitivity (−110 dBm at 1.2 kBaud)	Low current consumption (RX: 16.2 mA @ 1.2 kBaud, TX: 15.2 mA @ −6 dBm output power)
Programmable output power up to 10 dBm for all supported frequencies	Digital RSSI/LQI support
Frequency range: 300 – 348 MHz, 391 – 464 MHz and 782 – 928 MHz	

The CC1110 development kit was used to be our hardware test platform. IAR EW8051 is used as programming, downloading, and debugging tool. TI sniffer is used to trace the packet transmission for the entire wireless network. In our experiment, two CC1110 modules act as capsule devices. One module works as base station. Another one, connected to the computer with the Sniffer software, is used to monitor the entire communications.

5.2 Validating the Hardware

To validate that the hardware runs exactly the same as designed protocol and program, one hop communications using 802.15.6 and proposed protocol have been performed.

Fig. 5.1 shows the timing diagram of 802.15.6 which is captured by TI sniffer. In the beginning of the communication, BS sends the synchronization packet to the capsule devices. After the capsule receives the data, it starts to send a data packet to BS. Four slots later, the whole communication repeats. The hardware test matches the designed protocol and programs exactly.

Fig. 5.1 Timing diagram of star topology MAC captured by TI sniffer

The timing diagram of the hardware implementation based on the proposed MAC protocol is tested and shown in Fig. 5.2. Base station sends the sync packet in the beginning. Then a broadcast packet is sent by the BS. After the sensor receives the broadcast packet, it begins to broadcast its own information. In this experiment test it is assumed that BS believes there are four capsules in the network. Therefore, after four slots of receiving the power detection information, the sensor uploads the neighboring information to the BS. BS sends back the assignment back to the capsules. The capsule follows the schedule to send data packet. The hardware experiment matches the program exactly the same.

Fig. 5.2 Timing diagram of the hardware experiment

The captured time diagram above proves that the hardware runs the designed protocol as expected. Therefore, the experiment results based on this platform are credible.

To measure the network life time of the capsule network, button batteries are used as the power source of the CC1110 module. When the BS cannot receive data from the capsule under the monitoring of Sniffer, we assume that the capsule dies. A validation between the battery voltage and data transmission is conducted. The star topology TDMA is used. There are two slots totally within one frame. The BS sends a broadcast packet, and then the capsule sends a data packet with the packet size of 200 bytes.

A 3.6V button battery is used. The specification of the battery is shown in Table 5.2. A multimeter is connected to the button battery. It measures the voltage value every 30 seconds. On the other hand, the sniffer monitors the communication. Fig. 5.3 shows the relationship between the battery voltage and the successful data transmission. It

can be seen that when the voltage of battery drops below 3.3V, the BS cannot receive data any more. This result is exactly as we expected.

Table 5.2 Specification of the battery

Model	LIR845
Working voltage	3.6V
Capacity	12mAh
Diameter	8mm
Height	4.5mm
Weight	0.65g

Fig. 5.3 Validating the sniffer

5.3 Experiment Results

In the experiment, there are two capsules and one BS. For the BS, a finite state machine is used for the program as shown in Fig. 5.4. There are totally six states: synchronization, broadcast, power detection, uploading, schedule assignment, and data slots. The state is initialized as synchronization. After the BS transmits the sync packet, it turns into broadcast state. When the program checks the state and finds the state is broadcast, the BS starts to transmit the broadcast packet, and changes the state into “power detection”. In the next slot the program checks the power detection state and starts to receive the power detection data from capsules. Once the accumulate number of slots reaches number of capsules, the BS changes its state into “uploading”. In the next slot the BS start to receive the upload data. When the count of slots is equal to the number of capsules, the BS changes the state into “assignment”. In the assignment slots, the BS sends assignment to all the capsule devices, and then it turns into “data slot”. In the data slot section, the BS follows the schedules. When the count is equal to the number of capsules, the state is changed into “sync”. The procedure repeats again.

The flow chart for BS is shown in Fig. 5.5. After the radio is powered on, it initiates the data rate, frequency, timer, routing table, transmit power table and schedule table. The state is set to synchronization. The BS then goes into a while loop. It checks the state. If it is synchronization, BS initiates the network ID, device ID and sends the packet. The timer starts and state changes to broadcast. If the state is broadcast, the

broadcast packet is created with network ID, device ID and number of sensor nodes and then sent out. The state is changed to power detection. If the state is power detection, BS receives the data until the slot account is equal to number of sensor nodes. It changes the state into upload. If the state is upload, BS would receive until slot account is equal to number of sensor nodes. Then it changes the state into assignment. If the state is assignment, BS sends the calculated schedule for each sensor node and sends the schedule during the slot for certain sensor node. After this work it changes state into data slots. If the state is data slot, BS would follow the schedule until the end.

Fig. 5.4 Finite state machine for base station

Fig. 5.5 Flow chart for base station

Fig. 5.6 shows the finite state machine of capsule devices. The state is initialized as “sync”. When the capsule receives the sync data, it changes the state into “broadcast”. In the broadcast slot, after it receives the broadcast packet, it changes the state into “power detection”. In the power detection section, when the slot counter is equal to the number of capsules, the state is changed into “upload”. In the upload section, the capsule uploads its neighboring information. When the slot counter is equal to the number of capsules, the state is changed into “schedule assignment”. In the schedule assignment section, the capsule only wakes up in its own slot and receives the schedule. Once the counter is equal to number of capsules, the capsule turns into the state “data slots”. In the data slot section, the capsule follows the schedule and at last changes state into “sync”. The procedure repeats again. Fig. 5.7 shows the flow chart of the capsule device.

The flow chart is shown in Fig. 5.7. After the radio is powered on, it initiates the data rate, frequency and timer. The state is set to synchronization. The capsule then goes into a while loop. It checks the state. If it is synchronization, the capsule listens and receives data. If it is from BS and is sync data, the capsule starts the timer and changes state into broadcast. If the state is broadcast, the capsule listens and receives the broadcast packet. It retrieves the number of capsules. The state is changed to power detection. If the state is power detection, the capsule sends its own packet during its slot and listens for others' data during other slots. When the slot account is equal to the number of capsules, it changes the state into upload. If the state is upload, the

capsules send their neighboring table to BS during their own slots. Then it changes the state into assignment. If the state is assignment, the capsule receives schedule from BS during the slot for itself. After this work it changes state into data slots. If the state is data slot, BS would follow the schedule until the end.

Fig. 5.6 Finite state machine for capsule

Fig. 5.7 Flow chart for capsule

BS calculates the schedules for each capsule node. Schedule format is shown in Fig. 5.8. This schedule packet is sent to each sensor node from BS. It includes number of actions, state, txpower and nexthop ID. Num of actions represents the total actions during the data section of one frame. For each action, there are three states: TX, RX and sleep. If the state is TX, the BS would assign txpower and nexthop ID value. If the state is RX or sleep, txpower and nexthop ID are given a value of 0.

Num of actions	state	txpower	Nexthop ID	state	txpower	Nexthop ID	...		
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Fig. 5.8 Schedule format

When sensor nodes receive the schedule from BS during schedule assignment section, they analyze and store these data. At the beginning of each data slot, the capsule node checks the state. It follows the schedule to perform data transmission.

It is assumed that the capsule nodes are deployed in the human body. The nodes and BS are put in a straight line. The distances between node0 and node1, node1 and BS, node0 and BS are 20 cm, 20 cm and 40 cm, respectively. Node 1 is in the middle between node0 and BS. According to IEEE802.15.6 channel model, the path losses are randomly generated as 67 dB (node0-node1), 70 dB (node1-BS) and 85 dB (node0-BS). In the experiment, the nodes and BS are deployed in the air, but make the path loss between any two nodes the same value as above, to emulate the in-vivo scenario.

For the receive threshold, -84 dBm is adopted which is used in the simulation in Chapter 4. The transmit power is calculated the summation of receive threshold and the path loss value as shown in Eqn 5.1.

$$\text{Transmit power} = \text{receive threshold} + \text{path loss} \quad \text{Eqn. 5.1}$$

From the datasheet, CC1110 has a current consumption of 20.5 mA for receiving, 20 mA for transmitting with 0 dBm transmit power, 18.6 mA (estimated using curve fitting according to Eqn. 4.10) for -15 dBm transmit power and 5 mA for sleep states of transceiver. This 5 mA current is mostly consumed by embedded 8051 microcontroller. The battery is 3.6V. Data packet size is 200 bytes and the average control data size is 4 bytes. The parameters are listed in Table 5.3.

Table 5.3 Parameters used in hardware experiment

Parameters	Value	Parameters	Value
Current consumption in TX+0dBm	20 mA	Current consumption in TX-15dBm	18.6 mA
Current consumption in sleep	5 mA	Current consumption in RX	20.5 mA
Voltage	3.6 V	Number of capsules	2
Path loss model	802.15.6	Frequency	433 MHz
Control packet size	4 bytes	Packet size	200 bytes
Transmission power (dBm)	adaptive	Receive threshold	-84 dBm

The experiments of network life time for 802.15.6 and proposed TDMA are

conducted two times. The network life time are shown in Table 5.4. The average life time of proposed TDMA is 2938.5 s and 2916 s, which is slightly smaller than the life time of 802.15.6, 3046 s and 3049.5 s. From the sniffer, the routing from the capsule to BS for two capsules is 1 hop. 802.15.6 and proposed TDMA both have the same routing – from capsule to BS, but the proposed TDMA has more overhead due to control data, so the total energy consumption is larger than that of 802.15.6, therefore its life time is shorter.

Table 5.4 Experiment results of network lifetime

	experiment number	node 0	node 1	average	delivery ratio
802.15.6	1	3040s	3052s	3046s	99.98%
	2	3050s	3049s	3049.5s	99.8%
Proposed	1	2927s	2950s	2938.5s	99.93%
TDMA	2	2902s	2930s	2916s	99.87%

A simulation for this hardware experiment is conducted. The parameters in Table 5.3 are adopted. The result is shown in Fig. 5.9 and compared with experiment result of network life time. The simulation result matches the hardware experiment that the network life time of proposed TDMA is smaller than that of 802.15.6. The network life time in the simulation result is larger than that of experiment because of several reasons. First, the battery voltage in the experiment is 3.6 V which may lead to different consumed current, while the current consumption used in the simulation

refers to the datasheet in which the voltage is 3 V. Second, the current consumption in the simulation is for CC1110 chip only, while in the experiment the other components and the circuit board consume energy. From the figure it can also be seen that the error (difference between simulation result and experiment result) of proposed TDMA is slightly bigger than the error of 802.15.6. This is because the proposed TDMA has more transition of status which consumes extra energy but this part of energy consumption is not reflected in the simulation.

Fig. 5.9 Network lifetime for 802.15.6 and proposed TDMA

The reason that the proposed TDMA is less energy efficient is because the circuitry power consumption of CC1110 is too big. Therefore one hop is the best route. The proposed TDMA consumes more energy due to overhead. In the future if circuitry power drops to certain level (below 1mW), multi-hop communication will become meaningful and save energy compared with single hop. Then the proposed TDMA

would be a good choice for energy conservation.

5.4 Summary

This chapter discusses the hardware implementation of the proposed TDMA MAC protocol. The validation of the hardware proves that it works the same as expected. The finite state machine and flow chart for BS and capsule are given. The results show that the proposed protocol is successfully implemented on CC1110. The network lifetime of proposed protocol does not give advantage. This is because that the circuitry power of CC1110 is large compared to transmit power. In the future when the circuitry power reduces, the proposed protocol could be used for energy saving.

Chapter 6 Conclusion and Future Works

6.1 Conclusion

The key objective of this thesis is to design an energy efficient MAC protocol for multiple capsule networks. A TDMA based uplink, downlink asymmetric MAC protocol is proposed. The special asymmetric architecture as well as the adaptive power control reduces the energy consumption significantly. The optimization of the frame format further reduces the energy consumption on the capsule sides.

The wireless capsule endoscopy was introduced in the beginning of the thesis. It is a kind of medical device, which is swallowed by patients and capture the images of the GI tract. The images are sent wirelessly to the outside data recorder for diagnosis by doctors. A survey of the related technologies including wireless communication, localization, wireless power supply, active locomotion, has been conducted. From the development of WCE, it can be imaged that the future wireless capsule must be a kind of multi-functional robot. Low power consumption and miniature size are the biggest challenges. It is also very promising that more than one capsule, as well as other sensors, collaborate to finish some monitoring works. The capsules and the wireless receiver form a wireless network. The network protocols of this kind of networks become the research direction.

For this multiple capsule networks, energy consumption is the major concern. A good MAC protocol can efficiently reduce the energy consumption of the capsule devices. A comprehensive survey of MAC protocols for WSNs and BSNs was conducted. Besides the existing standard, many MAC solutions are proposed for reducing the energy consumption of the sensor devices. They use many different ways to let the sensor devices sleep as much as possible so as to minimize the energy consumption. The network topology is also mixed into the MAC protocol design to achieve better performance.

Multiple capsule networks are similar to the WSNs and BSNs, but the proposed MAC for WSNs and BSNs are not the best solution for multiple capsule networks because of the unique attributes of the multiple capsule networks such as mobility, small network area, severe path loss of human body, etc.. Based on the unique attributes of the multiple capsule networks, a specific MAC protocol is proposed.

Multi-hop communication through human body was investigated. The simulation results proved that multi-hop communication consumes less energy than single hop communication via human body when circuitry power is smaller than 1 mW, which is already achieved in lab design. Based on this result, a novel uplink, downlink asymmetric topology was proposed. For downlink data communication, star topology was adopted. The coordinator sends packet directly to the sensor devices. This is because the coordinator is outside human body without size constraints, while the

sensor devices are inside human body with strict size constraints. For uplink data communication, due to the limited energy contained in the capsule devices, a multi-hop communication was proposed. By this way, the energy consumption was reduced significantly.

The TDMA frame format was proposed in detail. The TDMA frame was divided into several sections: synchronization, broadcast, power detection, information upload, schedule assignment, and data slots. According to the broadcast information, the capsule devices exchange their information and record the RSSI. Then they upload the neighboring information to the coordinator. The coordinator calculates the best route, TDMA slot assignment, and transmit power, and sends these information back to the capsule devices. The capsule devices follow the schedule to complete the communication.

The simulation of the proposed MAC protocol and 802.15.6 draft were conducted using Qualnet with the random mobility pattern. The results showed that the proposed MAC protocol is better than 802.15.6 in terms of energy consumption when circuitry power is 100 μ W. The protocol was implemented on the hardware with the low power CC1110 in place. The experiment results matched the simulation results. The latency and overhead was optimized based on the original design.

The main contributions of this thesis are summarized as follow:

- A survey of technologies of wireless capsule endoscopy
- Literature review on MAC protocols of both WSNs and BSNs
- Proved that multi-hop communication can save energy consumption for in-vivo communication.
- Build up a simulation platform with random mobility pattern in the small intestine using Qualnet simulator.
- Proposed a MAC protocol for multiple capsule networks:
 - Asymmetric topology
 - Adaptive power control for mobile nodes
 - TDMA frame format
- Optimization on latency and overhead
- Hardware implementation of the proposed MAC protocol

6.2 Future Works

In the future, the proposed protocol will be implemented for the special designed wireless capsule endoscopy under the project. The hardware with the proposed MAC protocol may be tested for the in-vivo environment. The investigation and optimization of the slot assignment algorithm and power detection frequency will be continued.

For the slot assignment algorithm, different capsule devices may have different slot requests. The data rate may have a big range, from several Kbit to several Mbit. The

application may have several priorities. The priority is classified into different level of latency, or they may be classified into transmission reliability. The remaining energy of the capsule devices is different. Therefore, the algorithm should consider all of these and calculate the best route and best slot assignment. Delay is very important parameter in the slot allocation. This thesis did not consider too much about the delay performance, but it is very important for real time application. The optimization should be done in the future works. Another issue is the remaining energy. The routing and slot allocation algorithm should consider the remaining energy of the capsule devices, to extend the average life time. If one capsule device remains little energy, then give it less work and let it sleep longer time. Only the highest priority data is considered to be transmitted through it.

The optimization of power detection frequency can be conducted further. This thesis discussed the relationship between the power detection frequency and capsule moving speed. The algorithm can be designed based on this result in the future. First, according the changing position, estimate the speed of every capsule device. The speed for different capsules may be different. Secondly, use the estimated speed to calculate power detection frequency. Make sure the transmit power is big enough for a packet delivery ratio of 1. The pattern of the small intestine can also be considered to estimate the moving speed or power detection frequency.

Glossary

AC-MAC Adaptive Coordinated Medium Access Control

AI-LMAC Adaptive Information-centric and Lightweight Medium Access Control

ACK Acknowledgement

AEA Adaptive Election Algorithm

AP Access Point

BAN Body Area Networks

B-MAC Berkeley Medium Access Control

BSN Body Sensor Networks

CBR Constant Bit Rate

CMOS Complementary Metal Oxide Semiconductor

CSMA Carrier Sense Multiple Access

CTS Clear to Send

DCF Distributed Coordination Function

DDT Data Distribution Table

DIFS DCF Inter-Frame Space

DMAC Dynamic Medium Access Control

DSMAC Dynamic Sensor Medium Access Control

DSSS Direct Sequence Spread Spectrum

ECN Explicit Congestion Notification

FCC Federal Communications Commission

FDTD Finite-Difference Time-Domain

FHSS	Frequency Hopping Spread Spectrum
FRTS	Future Request to Send Message
GI	GastroIntestinal
GPS	Global Positioning System
GUI	Graphical User Interface
HCL	High Contention Level
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	International of Electrical and Electronics Engineers
ITU	International Telecommunication Union
LAMA	Link Activation Multiple Access
LCL	Low Contention Level
LEACH	Low-Energy Adaptive Clustering Hierarchy
LED	Light Emitting Diodes
MAC	Medium Access Control
MEMS	Micro-Electro-Mechanical Systems
MPE	Maximum Permissible Exposure
NAMA	Node Activation Multiple Access
NAV	Network Allocation Vector
NP	Neighbor Protocol
OGIB	Obscure Gastrointestinal Bleeding
PAMA	Pairwise-link Activation Multiple Access
PAN	Personal Area Networks

PCF	Point Coordination Function
PDR	Packet Delivery Ratio
PIFS	PCF Inter-Frame Space
QoS	Quality of Service
RF	Radio Frequency
RFID	Radio-Frequency Identification
RTS	Request to Send
RX	Receiving
SAR	Specific Absorption Rate
SEP	Schedule Exchange Protocol
SMAC	Sensor Medium Access Control
SYNC	Synchronization
TDMA	Time Division Multiple Access
TRAMA	Traffic-Adaptive Medium Access
TX	Transmission
UWB	Ultra-Wideband
WBSN	Wireless Body Sensor Networks
WCE	Wireless Capsule Endoscopy
WLAN	Wireless Local Area Networks
WPAN	Wireless Personal Area Networks
ZMAC	Zebra Medium Access Control

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