國立交通大學

資訊工程學系

碩士論文

適用於無線微型感測網路低延遲且低耗電之媒體存取控制協定

Latency-Aware and Energy-Efficient MAC Protocol for Wireless Sensor Networks

研究生：陳宗逸

指導教授：謝續平 博士

中華民國九十四年五月

適用於無線微型感測網路低延遲且低耗電之媒體存取控制協定

Latency-Aware and Energy-Efficient MAC Protocol for Wireless Sensor Networks

研 究 生：陳宗逸　　Student: Tsung-Yi Chen
指導教授：謝續平 博士　　Advisor: Dr. Shiuh-Pyng Shieh

國立交通大學
資訊工程學系
碩士論文

A Thesis
Submitted to
Department of Computer Science and Information Engineering
College of Electrical Engineering and Computer Science
National Chiao Tung University
In Partial Fulfillment of the Requirements
For the Degree of
Master
In

Computer Science and Information Engineering

June 2005

Hsinchu, Taiwan, Republic of China

中華民國九十四年五月

適用於無線微型感測網路低延遲且低耗電之媒體存取控制協定

研究生：陳宗逸　　　　　　　　　　指導教授：謝續平

國立交通大學　資訊工程學系

摘　要

無線微型感測網路是由一群具備極有限電力的無線微型感測器所組成，此種網路的目的是收集目標區域的特定資料，並將其回傳到基地台供管理者監測及控管。對無線微型感測網路來說，節省能源消耗以及縮短資料傳輸延遲是兩個非常重要的課題。在許多已完成的研究報告裡顯示傳輸資料是最為耗電的一個動作，天線模組是最耗電的元件，由於天線模組的動作被媒體存取協定控制，此提供了我們一個研究的切入點。本篇論文提出了一個同時能節省能源消耗並縮短資料傳輸延遲的媒體存取控制協定，現有宣稱能達到省電效果的媒體存取控制協定皆讓整個感測網路的感測器遵守同一個動作排程，所有的感測器會在同一時間將天線模組開啟並進行傳送資料的動作，在一段時間後同時將天線模組關閉以達到省電效果，此排程會讓所有感測器週而復始做此動作。雖然使用此排程的媒體存取控制協定的確可以達到省電的效果，但同時卻造成很嚴重的資料傳輸延遲。本篇論文所提出的媒體存取控制協定不要求所有感測器皆遵守同一排程，而是根據各個感測器的所在位置安排其獨有的排程，這個設計可以有效的減少資料傳輸延遲。除此之外為了讓我們提出的協定能適用於各種不同的網路流量及網路類型，我們提供了一個可將感測器排程使用的更靈活的機制，搭配此機制使用可達到最好的省電以及縮短傳輸延遲的效果。

Latency-Aware and Energy-Efficient MAC Protocol for Wireless Sensor Networks

Student: Tsung-Yi Chen　　Advisor: Shiuh-Pyng Shieh

Department of Computer Science and Information Engineering
National Chiao Tung University

Abstract

Wireless Sensor Networks (WSNs) are formed by a set of small devices with limited battery capacity, which collect sensed data and transmit it to the base station. Energy conservation and data transmission latency are considered two important issues. Among all operations, data transmission dominates the consumption of energy. In this thesis, we proposed a MAC protocol which can significantly reduce energy consumption and transmission latency. The existing MAC protocols use a unique periodical active/sleep schedule for the whole network to save energy. However, these protocols suffer long transmission latency. Rather than unifying the periodical active/sleep schedule of all sensor devices, we arrange the schedule of each sensor device according to its location on the data gathering tree. This arrangement can provide continuous data forwarding through active sensor devices. The energy consumption is also conserved during the periodical sleeping periods. To dynamically adapt to different traffic load, an adaptive sleeping scheme is proposed, which adjusts the active/sleeping schedule of each sensor device according to the traffic load. The simulation showed that the proposed MAC protocol obtains significant energy saving and reduces transmission latency.

誌謝

本篇論文的完成首先要感謝我的指導老師謝續平教授。感謝老師認真的指導以及給予許多寶貴的經驗與意見，也感謝老師不厭其煩的幫我修改文章，以致能有今天這份完整的畢業論文。

其次要感謝我的父母，感謝他們多年來辛苦的栽培，沒有他們在背後支持，今日我將無法得以在此完成本篇論文，感謝他們總在我疲憊的時候給予我最多的鼓勵，在我徬徨的時候指點我正確的方向。

此外要感謝分散式系統與網路安全實驗室的諸位學長姐、學弟妹與同學們，感謝他們在我論文撰寫過程給予的諸多幫助，其中我要特別感謝吳孝展、李卓育以及林亞正三位同學，因為有他們的督促以及經驗交流，我才能順利的通過碩士論文的考驗。

最後我要感謝的是所有在我求學過程曾經幫助過我的師長、朋友，感謝所有人給予我的關懷和照顧，這篇論文是我至今完成過 最棒的作品。

Table of Contents

List of Figures

1. Introduction

Wireless sensor networking is an emerging research area with potential applications in environmental monitoring [7, 9, 10], surveillance, military, health [22, 23] , and security. Such a network normally consists of a group of nodes, called sensor nodes. Each node has one or more sensors, an embedded processor, and a low-power radio. Typically, these nodes are linked by a wireless medium to perform distributed sensing tasks. This kind of sensor networks offers a monitoring capability in virtually any environment even if a wired connection is not possible or physical placement of the nodes is difficult.

1.1 Features of Wireless Sensor Networks

The major differences between wireless sensor networks and other wireless networks, such as Mobile Ad-hoc networks and cellular networks, are [1, 3, 26, 27]：

1. Critical of energy consumption： The small volume of sensor node causes the critical battery capacity. It may difficult to recharge the batteries of sensor nodes. The energy consumption becomes the most critical issue of the design of sensor node.
2. Low communication bandwidth： The bandwidth of wireless sensor network is about 20 – 150kb/s. This bandwidth is relative low to the tradition wireless networks.
3. Limited computing power and memory space: Due to the small volume and low cost of each sensor node, the computing power and memory space are critically

limited. There is only several kilo bytes to hundreds kilo bytes memory equipped on each sensor node. And the computing power ranges from 4MHz to 100MHz.

4. The large scale of deployment： Wireless sensor networks often consist of hundreds even thousands of wireless sensor nodes. Those sensor nodes are deployed in a large wired area for some monitoring task.

Beside the differences in physical layer, the data traffic flow in wireless sensor network is quite different from traditional wireless networks. Rather than many independent point-to-point flows, data traffic flow in wireless sensor networks is from the sensor nodes to a base station that collects the data. Besides this kind of data flow, there are several other kinds of data traffic patterns. Now we have identified three major kinds of traffic types. First type is the control packets or command packets from base station to sensor nodes. This kind of packets is used to control sensor nodes or to change sense mode, such as changing the temperature sense mode to humidity sense mode. Among all communication messages, this kind of control packets is rare and not delays sensitive. Second traffic type is the communication messages between two arbitrary sensor nodes. This kind of communication is often used to exchange information such as synchronization packets between sensor nodes. Third type is the most significant traffic in wireless sensor networks. This traffic is the data packets sensed by sensor nodes and move from nodes to centric data collector, the base station. This type of traffic is much more than other two types. The data delivery path will form a data gathering tree [5, 6, 25]. In order to transmit data more efficient, the construction of the data gathering tree has been studied under various circumstances [2, 4].

Another important sensor network characteristic is that traffic generation at each node either has to be periodic or event-driven. Some applications such as medical temperature monitoring system require periodic packet generation at each sensor node to monitor patients' condition [24]. On the other hand, the sensor network deployed for fire detection system needs packet generation only when fire breaks out. This is an event-driven sensor network. Furthermore, shortening data packet transmission latency is also important in wireless sensor networks [36]. Many applications are latency sensitive and even require real-time delivery guarantee. For example, suppose a wireless sensor network is used for security monitoring. It must be necessary to know when and where a security breach occurs in a short time. Even if real-time delivery is not required (e.g. habitat monitoring [7]), it will be good to transmit all the packets as soon as possible.

1.2 Medium access control protocol

Like in all shared-medium networks such as wireless networks and Ad-hoc networks, medium access control (MAC) is an important technique that enables the successful operation of the network. The fundamental task of MAC protocol is to avoid collisions from interfering nodes. There are many different kinds of MAC protocol have been presented. Typical examples are the code-division multiple access (CDMA), time-division multiple access (TDMA), and contention-based MAC protocols such as IEEE 802.11 CSMA.

To design a good MAC protocol for the wireless sensor networks, we have considered the following requirements ：

1. Energy efficiency： The limitation of the sensor nodes in terms of energy

resources due to their small size and long lifetime requirements also imposes constraints on the MAC protocol design. Sensor nodes are battery powered and often difficult to change or recharge batteries. In fact, someday we expect sensor nodes to be cheap enough that they are discarded rather than recharged. Prolonging network life for these sensor nodes is a critical issue. Radio is the most energy consuming component in a sensor node. The primary sources of energy waste in the radio of a sensor node are collisions, overhearing, and idle listening. When a transmitted packet is corrupted, it has to be discarded. Since this packet is discarded, it needs to be retransmitted. The energy consumption per successful transmission will increase. Overhearing occurs when a node consumes energy to receive a packet that is not destined to it. Finally, the major source of power inefficiency is idle listening. In many MAC protocols such as IEEE 802.11, the nodes listen to the channel continuously in order not to miss packets destined to them. As a result, the nodes listen to the channel although there is no packet in the channel at all. If nothing sensed, sensor nodes are in idle listening mode. However, listening to the channel costs almost as much power as receiving packets. For example, Stemm and Katz [12] measure that the power consumption ratio of idle：receiving：transmission is 1:1：05：1.4 on the 915MHz Wavelan card. And the Digitan wireless LAN module (IEEE 802.11/2Mbps) specification shows the ratio is 1：2：2.5 [13]. On the Mica2 mote, the ratio for radio power draw is 1：1：1.41 at 433MHz with RF signals power of 1mW in transmission mode. Therefore, to conserve energy, sensor nodes must only be awake to receive the packets destined to them or to transmit, and sleep otherwise.

2. Latency awareness： Latency refers to the delay from when a sender has a

packet to send until the packet is successfully received by the receiver. Many applications require the guaranteed arrival of sensed data to base station within a specific deadline. An example of security monitoring is mentioned earlier. Another example is fire detection system. In fire detection system, sensor nodes are placed in different area to sense the local temperature and transmit the information to base station. When fire breaks out, it may be only several minutes for people to run away. Thus MAC protocol should be able to guarantee an upper bound of three minutes of the maximum delay from the sampling of the sensors until the time when data reaches base station. Only if the sensed data be transmitted as soon as possible, the appropriate reaction could be taken.

3. Fairness： Fairness reflects the ability of different users, nodes, or applications to share the channel equally. In traditional wireless network, each user requires equal time and chance to access the communication medium. Fairness is quite an important issue in tradition networks. However, in wireless sensor networks, all nodes are dedicated to a single common task. At some particular time, one node may have dramatically more data to send than some other nodes. In this case, fairness is not important as long as application-level performance is not degraded. Hence, rather than node level fairness, we focus on maximizing system-wide application performance.
4. Throughput： Throughput (often measured in bits or bytes per second) indicates the amount of data successfully transmitted from a sender to a receiver in a given time. In wireless sensor networks, throughput means the amount of packets successfully received by base station in a fixed interval. Many factors affect the throughput, including efficiency of collision avoidance, channel utilization, latency and control overhead. As with latency,

the importance of throughput depends on the application. Our proposed scheme tries to maximize network throughput and reduce transmission latency.

1.3 Contributions

The objective of this thesis is to propose a latency aware and energy efficient medium access control protocol, the LAMAC protocol, for wireless sensor network. Although there are some MAC protocols proposed to stress the energy conserving for sensor networks. However, these works trade transmission latency for energy saving. The trade-off results in long transmission latency which is too long to be ignore. There is little work has been proposed to deal with this problem. In this thesis, we proposed a MAC protocol which reduces both transmission latency and energy consumption. We let sensor nodes to perform periodical active and sleep to reduce energy consumption. The active-sleep schedules of nodes are staggered in order to provide a continuous forwarding routing path through active sensor nodes. By arranging the schedule, we can reduce the transmission latency greatly. Besides this, the staggered schedule can also reduce the medium competitors of each sensor node. With fewer competitors, sensor nodes will have higher probability to win the medium and save more energy wastage. We also proposed a technique, called adaptive sleeping, for the proposed LAMAC protocol to adapt different traffic load. The adaptive sleeping technique can switch low-duty-cycle mode to a more active mode under high traffic load. By using this technique, we can reduce much more transmission latency. Finally, the proposed LAMAC protocol has quite good adaptive ability to sensor network which is unreliable in data transmission.

1.4 Synopsis

The rest of this thesis is organized as follows： The related work of the existing MAC protocols will be presented in Chapter 2. In Chapter 3, we will describe the proposed MAC protocol. In Chapter 4, some analysis of transmission latency will be presented to show the improvement of the proposed protocol. In section 5 we will show the performance of the proposed protocol through simulation. Finally we will make a conclusion in Chapter 6.

2. Related work

The medium access control protocol is a broad research area. There have been some MAC protocols works in the new area of low-power and wireless sensor networks. Current MAC protocols can be broadly divided into two groups： Schedule-based and Contention-based protocols. These two groups of MAC protocols have their own advantages and disadvantages. But the contention-based protocols are more suitable for wireless sensor networks compared with schedule-based protocols. Now we have identified these two classes of medium access control protocols.

2.1 Schedule-based MAC protocols

The first class of medium access control protocols is based on reservation and scheduling. Among protocols in the first class, TDMA has attracted attentions of sensor network researchers. In TDMA, the channel is divided into N time slots. Each slot is used for only one node to transmit. The N slots comprise a frame, which repeats cyclically. Figure 2.1 shows an example of TDMA frame. Currently, TDMA is used in cellular wireless communication networks such as GSM system [15]. In the cellular networks, each cell has a base station to collect data packets. These base stations allocate time slots and provide timing and synchronization information to all mobile nodes. Mobile nodes only are able to communicate with base station. There is no peer-to-peer communications between mobile nodes within these cellular networks. TDMA has a natural advantage of energy conservation compared to contention protocols, because the duty cycle of the radio is reduced and there is no contention-introduced overhead and collisions.

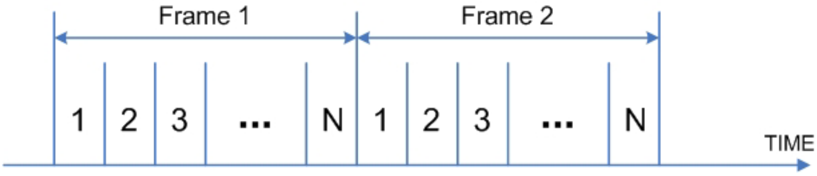

Figure 2-1： TDMA divides the channel into N time slots

However, using TDMA usually requires mobile nodes to form real communication clusters [16, 17, 18, 19], analogous to the cells in the cellular communication systems. One node within the cluster is selected as the cluster head, and acts as the base station. Nodes can only communicate with the cluster head. Within a cluster, peer-to-peer communication is not directly supported. Managing inter-cluster communication and interference is not an easy task and may need some other approaches such as CDMA or FDMA to accomplish. Moreover, when the network topology or the number within a cluster changes, it is quite difficulty for TDMA to modify its frame length and time slot assignment. Frame length and static slot allocation also limit the maximum number of active mobile nodes in any cluster. For example, Bluetooth clusters can only have at most 8 active nodes. Thus the scalability of TDMA is normally not as good as contention-based protocol and may be not suitable for wireless sensor networks.

SMACS (Self-Organizing Medium Access Control for Sensor Networks) and EAR (Eavesdrop-And-Register) [20] protocol are proposed to achieve power conservation based on TDMA-FDMA combination. Each node maintains a TDMA-like frame, called super frame, where it schedules different time slots to communicate with its known neighbors by generating transmission/reception schedules during the connection phase. Each node either talks to one of its neighbors or sleeps at each time slot. The interference between adjacent links is avoided by assigning different channels to potentially interfering links with FDMA or CDMA. The EAR algorithm is then used to enable seamless connection of mobile nodes in the network. Although the structure of super frame is similar to a TDMA frame, SMACS does not avoid two interfering nodes from accessing the medium at the same time. The actual multiple accesses are accomplished by FDMA or CDMA manner. The drawback of this algorithm is that it requires extra hardware and abundant bandwidth for nodes to tune the carrier frequency.

LEACH (Low-Energy Adaptive Clustering Hierarchy) [21] is also an example of schedule-based protocol in wireless sensor networks. LEACH organizes nodes into cluster hierarchies, and applies TDMA scheme within each cluster. One node will be elected to be the cluster head in each cluster. And the cluster head is rotated among nodes with the same cluster according to their remaining energy levels. Sensor nodes only can communication with the cluster head. The advantages and disadvantages of LEACH are similar as TDMA.

2.2 Contention-based MAC protocols

Instead of dividing the medium into sub-channels in schedule-based MAC protocol, the communication medium is shared by all nodes in contention-based MAC protocol. The contention-based MAC protocols provide different kinds of contention mechanism for mobile nodes to decide which node has the right to access the communication medium at any particular time. The medium is allocated on-demand. This kind of MAC protocols has several advantages compared to schedule-based MAC protocols. Whenever the node density or data traffic changes, the contention-based MAC protocols can easily adapt to these change because that the resources are allocated on-demand. And this kind of MAC protocols also can adapt to network topology changes. This is because no communication clusters are required. Thus no matter how network topology changes, the contention mechanism could still work as well. Finally, contention-based MAC protocols do not require fine-grained time synchronizations as in schedule-based MAC protocols. This is an important advantage because time synchronization is not an easy task in wireless sensor networks.

The major disadvantage of a contention protocol is its inefficient usage of energy. As mentioned in introduction： The nodes listen to the channel continuously in order not to miss packets destined to them. Thus they will waste a lot of energy in idle listening and receiving packets which are not destined to them. Besides the idle listening problem, transmission collision and contention mechanism also consume some energy. To design a good contention-based MAC protocol for long-lived wireless sensor networks, overcoming these disadvantages is necessary.

The popular IEEE 802.11 CSMA [29] for wireless networks is a contention-based protocol that can be operated in ad-hoc mode. It is mainly built on the research protocol MACAW [30]. It is widely used in ad hoc wireless networks because of its in-band signaling (through RTS/CTS messages) to reduce collisions caused by so-called hidden node problem. Some works [31] have shown that the energy consumption using this MAC is very high due to the idle listening problem. Thus it includes a power-saving mode in which individual nodes periodically active and sleep. However, the 802.11 protocol is designed with the assumptions that all nodes are located in a single network cell. It is not adaptive to multi-hop networks because it requires more complexity and dynamic state than would generally be available in wireless sensor networks.

PAMAS [32] avoids overhearing by putting nodes into sleep state when their neighbors are in transmission. It uses two channels, one for data and one for control. All control packets are transmitted in the control channel. Because of the two channel scheme, PAMAS requires two independent radio channels, which indicates two independent radio modules on each node. PAMAS still has idle listening problem. The similar protocol with two channel radio is [33].

Recently some MAC protocols using periodically active/sleep schedule to achieve great energy efficiency. The most famous protocol is S-MAC [34] which uses the RTS-CTS scheme to prevent overhearing. This protocol affects the proposed scheme greatly and we will discuss it shortly. T-MAC [8] seeks to eliminate idle energy further by adaptively setting the length of the active portion of the frames. Rather than allowing messages to be sent throughout a predetermined active period, as in S-MAC, messages are transmitted in bursts at the beginning of the frame. If no "activation events" have occurred after a certain length of time, the nodes set their radios into sleep mode until the next scheduled active frame. Activation events include the firing of the frame timer or any radio activity. STEM [35] protocol reduces energy consumption by combining the active/sleep schedule as well as a separate radio. The purpose of using a separate channel is to prevent control messages from colliding with ongoing data transmissions. This scheme is effective only for scenarios where the network spend most of its time waiting for events to happen.

Although the periodically active/sleep MAC protocols mentioned above all achieve great energy saving. They all have a common disadvantage which is the long transmission delay. A sensor node can not receive or send data packets when it is in sleeping mode. Since a sender must wait until the receiver wakes up before it can transmit the packet, the transmission latency increases. However, in order to attain good energy efficiency, the sleeping period is often tuned to be very long. This makes transmission latency more seriously. The proposed LAMAC protocol aims to eliminate the latency as well as energy consumption.

Finally, we look at the S-MAC protocol which is the most related work to our proposed protocol. The S-MAC（An Energy-Efficient MAC Protocol for Wireless Sensor Networks）was proposed by W. Ye, J. Heidemann and D. Estrin. The basic design of this contention-based MAC protocol is that time is divided into relatively large frames. Every frame has two parts： an active part and a sleeping part. During the sleeping part, a node turns off its radio to save energy. During the active part, it can communicate with its neighbors and send any messages queued after the active part. Figure 2(a) shows a basic structure of frame with no packets to send and Figure 2(b) shows a frame with packets to send. Since all nodes are active in the active part and only remain active when there are packets to send in sleeping part, the energy wasted on idle listening is reduced. In S-MAC the frame length is tuned to be much larger than active part. The active part is 1~10% of a frame.

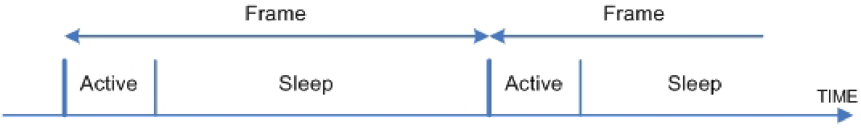

Figure 2-2 (a)： Frame Structure with no Packets to Send

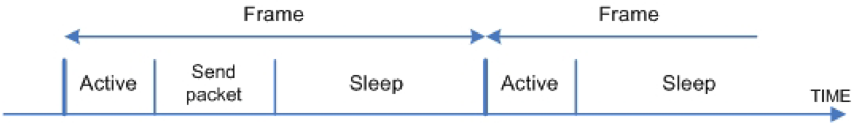

Figure 2-3 (b)： Frame Structure of S-MAC with packet to send

Figure 2-2： Frame Structure of S-MAC

S-MAC needs time synchronization between sensor nodes, but that is not as critical as in schedule-based protocols because the time scale is much larger with typical frame times in the order of 300 ms to 1 second. S-MAC uses a synchronization scheme called virtual clustering synchronization, in which nodes periodically send special SYNC packets to keep synchronized. All exchanged timestamps are relative rather than absolute. S-MAC uses the RTS/CTS/DATA/ACK signaling technique from 802.11 as its contention mechanism. It also uses this technique to reduce the number of collisions caused by the hidden-node problem. S-MAC uses the similar overhearing avoidance technique from the PAMAS protocol. The difference between these two techniques is that S-MAC uses in-band signaling (i.e., overhearing RTS/CTS packets). S-MAC also includes message passing support to reduce protocol overhead when streaming a sequence of message fragments.

Although S-MAC gets great energy saving, it still has two disadvantages. First, the packet transmission latency becomes very long with using S-MAC. There are several sources of latency in S-MAC including carrier sense latency、back-off latency、transmission latency、propagation latency、processing latency and queuing latency. But the major source is sleeping latency. As mentioned earlier, since a sender must wait until the receiver wakes up before it can transmit the packet, the transmission latency increases. Even if S-MAC uses a technique called adaptive active to reduce transmission latency, the latency is still very long. In some applications, this latency could not be tolerated. For example, a wireless sensor network with 100 sensor nodes deployed in a museum for fire detection. If all sensor nodes get packets to transmit at the same time, as the design of S-MAC, it needs about 10 to 30 minutes to collect all these data packets. If one of these data packets contains a fire alarm signal, this packet is supposed to be transmitted to the base station with 15 minutes delay. The museum may have been burnt down by the fire before this packet reaches the base station. We need a MAC protocol that can eliminate the latency as well as energy consumption. And this is the basic idea of our scheme.

3. Proposed Scheme

In this section, we will present our proposed Mac protocol, the LAMAC protocol. We will describe our assumptions about network and application first. Then the detail of LAMAC will be described.

The primary characteristic of wireless sensor networks is that all data packets move from sensor devices to a centric data collector through a data gathering path tree. The proposed MAC protocol exploits this characteristic to meet the energy and latency requirements. The existing MAC protocols use a unique periodical active/sleep schedule for the whole network to save energy. However, these protocols all suffer long transmission latency. Rather than unifying the periodical active/sleep schedule of all sensor devices, we arrange the schedule of each sensor device according to its location on the data gathering tree. This arrangement can provide continuous active sensor devices for data forwarding. The energy consumption is also conserved by the periodical sleep periods. We further introduced a technique called adaptive sleeping scheme for the proposed MAC protocol to adapt different traffic load. This scheme adjusts the active/sleep schedule of each sensor device according to the traffic load.

3.1 Network structure and application assumptions

Sensor networks are somewhat different than the traditional wired and wireless networks. And it is also different to ad hoc networks of laptop computers. We summarize our sensor network structure and application assumptions below.

The sensor networks are expected to be composed of many small sensor nodes. These nodes are deployed in an ad hoc fashion. The large number of nodes can take advantage of short range and multi-hop communication instead of long range communication to conserve energy [11]. There is a centric base station in our sensor networks. This base station acts as a collector to gather all the sensed data which is generated by the sensor nodes. All sensor nodes will collaborate to sense or monitor some targets assigned by the base station. The major data flow in the network is the sensed data propagate from sensor nodes to the base station.

We expect most sensor nodes to be dedicated to a single application or a few cooperative applications. Hence, rather than node level fairness, we focus on maximizing system-wide application performance.

Since sensor networks are designed to one or a few applications, the application-specific codes could be distributed through the network and activated when necessary. Intra-network processing is critical to achieve in sensor networks. Intra-network processing implies that data will be processed as whole messages at a time by store-and-forward manner. This processing leads to increase a significant latency because of waiting all of the message fragments to form the whole messages.

According to sensing or monitoring some specific targets, the sensor nodes are assumed to be fixed without mobility. Hence the network topology is stationary. Each sensor node has its own routing path toward base station. All routing paths form a data gathering tree. Because of the static topology, the data gathering tree remains stable for a quite long period of time.

In application assumptions, we expect that the traffic load of the sensor networks is dynamic. And the network applications require power efficiency and are latency sensitive. Examples of these are military surveillance, factory monitoring, fire detection, and security monitoring applications. This kind of applications will be vigilant for long periods of time, but rarely inactive until something is detected. When some event happens such as fire breaks out, it is necessary for base station to get the packets which are generated by the sensor nodes that are responsible for the fire as soon as possible. Thus, the applications are latency sensitive.

A scenario example is a fire detection system used in museum as shown in Figure 3-1. Figure 3-1 (a) shows the appearance of this museum and Figure 3-1 (b) shows the floor plan. The building is divided into several rooms. Each room contains one or more sensor nodes. There are also some sensor nodes outside the building to detect the temperature around the museum. In the control room, a base station is set up to receive wireless packets. In Figure 3-1 (b), the satellite-like objects denote the sensor nodes. And the dotted lines denote the relay paths which data propagate along. These sensor nodes detect the temperature in their spot by using thermistor sensor and relay this information to base station. Base station provides guard the information about the temperature of each room. The primary requirement in this application is real-time delivery guarantee of packets so that the guard could take reactions as soon as possible.

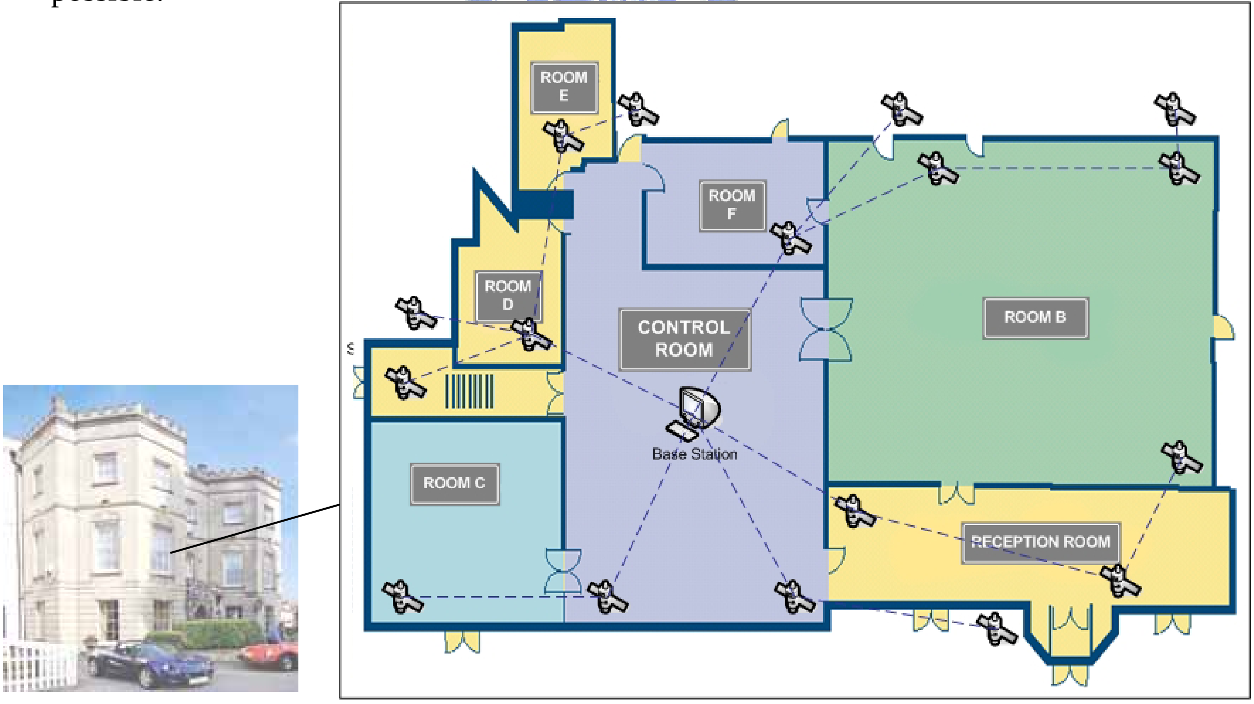

Figure 3-1： Scenario Example - Fire Detection System

These assumptions about the network and application affect the proposed LAMAC protocol design strongly. It also motivates the differences of LAMAC from the existing protocol such as S-MAC.

3.2 Basic Scheme

The major cause of transmission latency in S-MAC is the sleeping latency. When a sensor node gets a packet to send, it must wait until its receiver wake up. In the design of S-MAC, each frame is much larger than the active slot. If a node gets a packet right after the active slot, it must wait almost the whole frame time to transmit this packet. Even in an average case, it still needs to wait halt of the frame. The larger the frame, the longer the latency. If the intended receiver can wake up just at the moment that some other node wants to send packets to it, the sleeping latency will be eliminated. This is the main idea of LAMAC. We use a stair-like scheduling MAC protocol to achieve this goal.

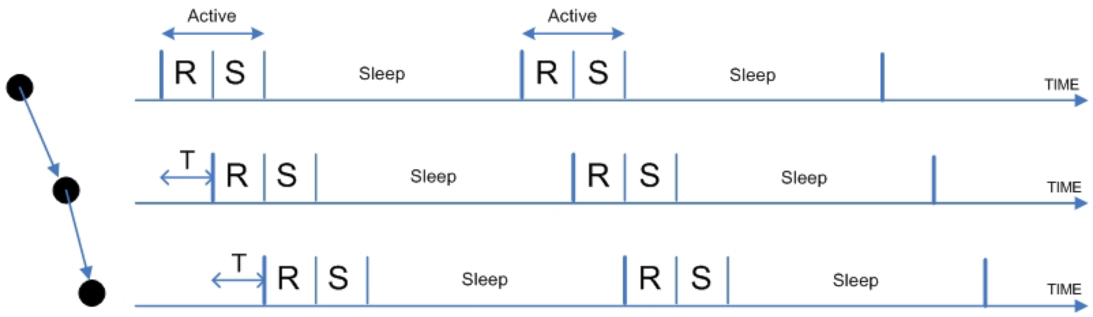

Figure 3-2： Data forwarding path and Stair-like Wake-up schedule

Figure 3-2 shows a data forwarding path and its stair-like wake-up schedule. We use the similar frame structure with S-MAC. Each frame is divided into two periods.

One is active period which is also called the duty cycle and the other is sleeping period. The difference between our frame from S-MAC is that the active period is further divided into two slots, the receiving slot and the sending slot. In Figure 3-2, the R slot denotes the receiving slot. And the S slot denotes the sending slot. In sending slot, nodes contend for the communication medium. Then the winners send their packets to their next hop nodes. In receiving slot, nodes wait for neighbors to send packets to them. In sleeping period, nodes turn off their radio to save energy. The sending slot and receiving slot both have length of T. This length is long enough for nodes to contend for the medium and transmit one packet. Along the data forwarding path, an offset of T is used to schedule the wake-up time. Each receiver on the path wakes up T interval later than its sender. This means that each receiver will wake up just at the moment that its sender enters the sending slot. The advantage of this schedule is that once a node receives a packet from another node, it can immediately enter the sending slot and transmit this packet to next hop node.

According to our assumptions about network data flow, every data packet in the network has a forwarding direction toward base station. Base station acts as a collector to gather all data packets in the network. Because base station is the root of the data gathering tree, every routing path ends in base station. This topology gives us a convenience to arrange the wake-up schedule of the whole network. Every node has an offset length T of wake-up time according to its hop count away from base station. Because of the infinite power, base station is always at receiving state without sleeping. So the wake-up time of the nodes which are one hop away from base station does not have offset. In our schedule design, these nodes wake up for the first time when the system start. Their schedule is called the base schedule. The nodes which are two hops away from base station have an offset T to the system starting time. And the nodes which are three hops away have an offset 2T. More generally, the node which is k hops away from base station has an offset (k-1)T of wake-up time to the system starting time.

3.2.1 Contention Mechanism

In wireless sensor networks, if more than one neighbor node wants to transmit packet, they need to contend for the transmission medium to avoid collision. Among contention based protocols, S-MAC does a good job in designing the contention mechanism. We use the similar mechanism with SMAC.

The contention mechanism uses a Request-To-Send（RTS）, Clear-To-Send（CTS）, Acknowledgement（ACK） scheme, which provides both collision avoidance and reliable transmission. Before transmitting a packet, physical carrier sense is performed at the physical layer by listening to the medium for possible transmissions of other packets. For example, if a sensor node wants to send a packet, it starts carrier sense when it enters the send slot. It randomly selects a time slot within a fixed contention window to finish its carrier sense. By the end of the random time, if the node has not sensed any transmission, it wins the medium and starts sending its RTS packet to the receiver. But if the node senses another transmission before the random time slot ends, it considers itself to lose the medium. The node then goes to sleep and wakes up at the next active period. Another losing case is when a sensor node sends RTS packet but fails to receive CTS packet. This means there is a node which is outside its communication range but has the same intended receiver with it wins the contention.

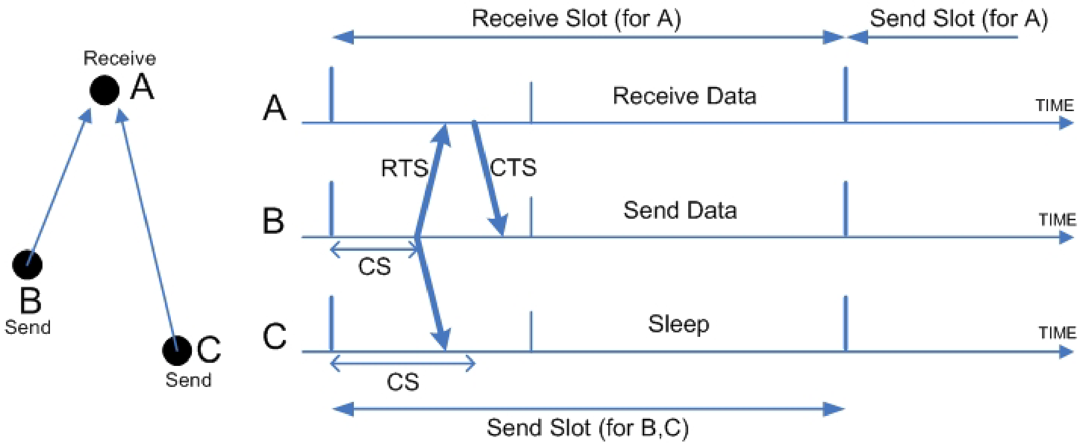

Figure 3-3： An example of contention process

An example is shown in Figure 3-3, node B and C both want to send packets to node A at the same time. Node B and C are in the same collision domain. They first generate a random carrier sense time which is denoted by CS in the figure to perform carrier sense. Because of the shorter CS time, node B is able to send the RTS packet to node A by the end of the CS. As long as node C senses the RTS packet from node B, it considers itself to lose the medium. Node C then ends carrier sense and goes to sleep. After receiving the CTS packet, node B starts the data packet transmission.

In addition to collision avoidance problem in the same collision domain, the hidden node problem is well known in wireless and ad hoc networks. This is what we mentioned above about a node outside some other node’s communication range but has the same receiver with it. The RTS-CTS scheme is sufficient to solve this hidden node problem. Although there is a little overhead of using this scheme, the overhead is worthwhile comparing with significant energy used in retransmitting packets.

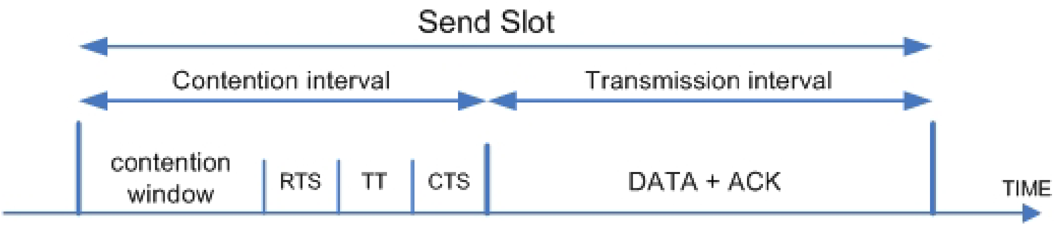

Figure 3-4： Structure of Send slot

3.2.2 The structure and length of active period

The active period is divided into sending slot and receiving slot. These two slots have the same length. Here we take sending slot as our example.

Figure 3-4 shows the structure of sending slot, the sending slot is divided into two intervals. One is contention interval and the other is transmission interval. As mentioned earlier, a node should perform carrier sense before sending a packet. It randomly generates a time slot within a fixed contention window to finish its carrier sense and then send its RTS packet. After sending its RTS packet, the node waits for CTS packet from the receiver. When it gets CTS packet, the contention mechanism finishes. The contention interval must be long enough to contain all these process. This observation gives us a limit on the length of the contention interval：

$$\text{The length of contention interval} = W + R + T + C$$

where W is the length of the fixed contention window, R is the length of an RTS packet, T is the turn-around time（the short time between the end of the RTS packet and the beginning of the CTS packet）, and C is the length of an CTS packet.

The transmission interval is responsible for data packet transmission. The length of the interval must be long enough to transmit a whole data packet and an acknowledge packet. The contention interval plus the transmission interval is the sending slot. And the receiving slot has the same length with send slot. Thus the active period is twice the length of the sending slot. In our stair-like wake-up schedule, the offset T is exactly the length of the sending slot.

3.2.3 Maintaining Synchronization

Since LAMAC is contention-based protocol, neighboring nodes which are in the same hop count must synchronize to contend the communication medium. The clock drift on each node can cause synchronization errors. Two techniques are used to make it robust to such errors. First, the active period is significantly longer than clock drift. Some experiments have shown that the clock drift between two nodes does not exceed 0.0002 s per second. Mostly the active period is more than 10^4 times longer than the clock drift rates. Compared to TDMA schemes with very short time slots, LAMAC requires much looser time synchronization. Second, all exchanged timestamps are relative rather than absolute.

Although the long active time can tolerate clock drift, neighboring nodes still need to periodically update their schedules with each other to prevent long-term clock drift. The synchronization scheme we used is similar to S-MAC. As described in the related work chapter, schedule synchronization in S-MAC is accomplished by sending a SYNC packet. The SYNC packet is very short, and includes the address of the sender and the time of its next sleep. The next sleep time is relative to the moment that the sender starts transmitting the SYNC packet. When a receiver gets the SYNC packet, it adjusts its timer according to the value in SYNC packet. We have modified this scheme to fit the proposed protocol. Instead of sending SYNC packets, we use the CTS packet to do the same thing. Each CTS packet contains a field to indicate the time of its next sleep. The time is also relative rather than absolute. We can reduce the

SYNC period in S-MAC without using SYNC packet. This makes LAMAC more energy efficient.

3.2.4 Scheme of data gathering tree construction

In the proposed LAMAC protocol, every node has a specific wake-up schedule according to its hop count from base station. Thus we need some information to recognize the position of all nodes in their routing path. Sensor nodes can adjust their wake-up schedule to the position. It means we need to construct data gathering tree of the whole network to locate sensor nodes.

There are some data gathering tree construction schemes mentioned in Chapter I. We use the similar scheme with" NeuRFon Netform " which is presented by L. Hester and Y. Huang. They construct data gathering tree according to the hop count of each node.

In the beginning of construction period, every node listens for beacon packets. The first node to start the construction, the base station, begins to broadcast beacon packets. These packets contain two fields. One is ID field which indicates the sender's ID, and the other is depth field which indicates the hop count of the sender from base station. The nodes which are able to receive these beacon packets form base station are within the communication range of base station. They can communicate with base station without intermediate nodes. After receiving the beacon packets, the nodes send connection request packets to base station. These packets contain the sender's ID and are used to request the base station to be its parent node. Base station will reply connection response packets to these nodes to accept the requests. Each node which has received reply takes base station to be its parent and sets its level to 1. All of the nodes which are one hop away from base station form the level-1 nodes. Then these level-1 nodes broadcast their own beacon packets include their ID and level. In our data gathering tree, the level of a node means its hop count from base station. The same procedures are performed between level-1 nodes and those nodes which are able to receive beacon packets. After the procedures finish, these nodes will from level-2 nodes. The construction procedure repeats until all sensor nodes have their own level and parent. The detailed description of the construction scheme is shown in Figure 3-5.

In the data gathering tree, the level-1 nodes are those which are within the communication range of base station. And level-2 nodes are those which are within the communication range of level-1 nodes but are outside of the range of base station. More generally, level-m nodes are those which are within communication range of level-*(m-1)* nodes, but are outside the range of base station, the level-1 nodes, the level-2 nodes, …, and the level-*(m-2)* nodes. Every node, with the exception of base station, has a single parent node, which is a node within its communication range and is one level higher than this node.

Each sensor nodes will keep a list which is called “upper layer list”. This list indicates the nodes which are one level higher and can be accessed by the owner of this list. Sensor nodes will construct this list during tree construction period. For example： After level-*k* nodes finish their construction procedure, level-k nodes will broadcast their own beacon messages which contain their ID and level to construct level-*(k+1)* nodes. Sensor nodes which receive the beacon messages from level-*k* nodes will be the level-*(k+1)* nodes. When sensor nodes receive these beacon messages, they will add the owners of beacon messages into their “upper layer list”. After the level-*(k+1)* nodes construction procedure finishing, each level-*(k+1)* nodes will also complete the “upper layer list” construction.

Notation：

SN： Sensor nodes
level： The hop count between sensor nodes and base station
ID：Unique identity of sensor nodes
Q-Message： Connect request message；used to build a link
P-Message： Connect response message；used to response *Q-Message*
BS： Base station

Initial State：

```
The level of all nodes = infinite
The level of BS = 0
```

Tree Construction State：

```
For k = level 0 to level n
    Level k SN broadcast beacon messages include their ID and level
    SN which receives message sends Q-Message back
    Level k SN reply P-Message
    SN which receives P-Message takes the sender to be its parent node, sets its level to (k+1) and replies an ack message to its parent.
```

Figure 3-5： Data gathering tree construction algorithm

When the data gathering tree construction process completed, each sensor nodes can arrange its own wake-up schedule according to its level on the routing path.

However, some links between sensor nodes may be broken due to the unreliable feature of wireless sensor networks. Harsh environment is one source of unreliability. Besides this, sensor nodes may fail due to some reason such as energy exhaustion. These unreliable features may cause the data gathering tree to lose its connectivity. Thus, the data gathering tree needs to be reconstructed every a specific interval.

However, data gathering tree reconstruction may cause some overhead such as energy and transmission latency. This is because when network is in reconstruction mode, data packets need to be queued in sensor nodes instead of forwarding to the base station. Sensor nodes have to keep waking up to process beacon messages in the whole tree reconstruction period. These overheads have to be reduced as possible. Thus, we simulate the overheads caused by different reconstruction interval. We uses 4 conditions to simulate these overhead. The condition of"10% nodes failure" indicates that every a specific interval, there will be 10% nodes losing their function and can not forward and process any data packets any more. The other conditions are similar. The results are shown in Figure 3-6 and 3-7. As shown in Figure 3-6, when reconstruction interval is short such as 20 seconds or 35 seconds, the advantage of tree reconstruction is not obvious. Especially when node failure rate is 10%, the overhead of transmission latency caused by short reconstruction interval becomes too serious to be accepted. As the result shows, the interval of 95 seconds may be an acceptable interval. Figure 3-7 shows the overhead of energy consumption. The similar conclusion of 95 seconds interval is also made. Thus, we will reconstruction our data gathering tree every 95 seconds.

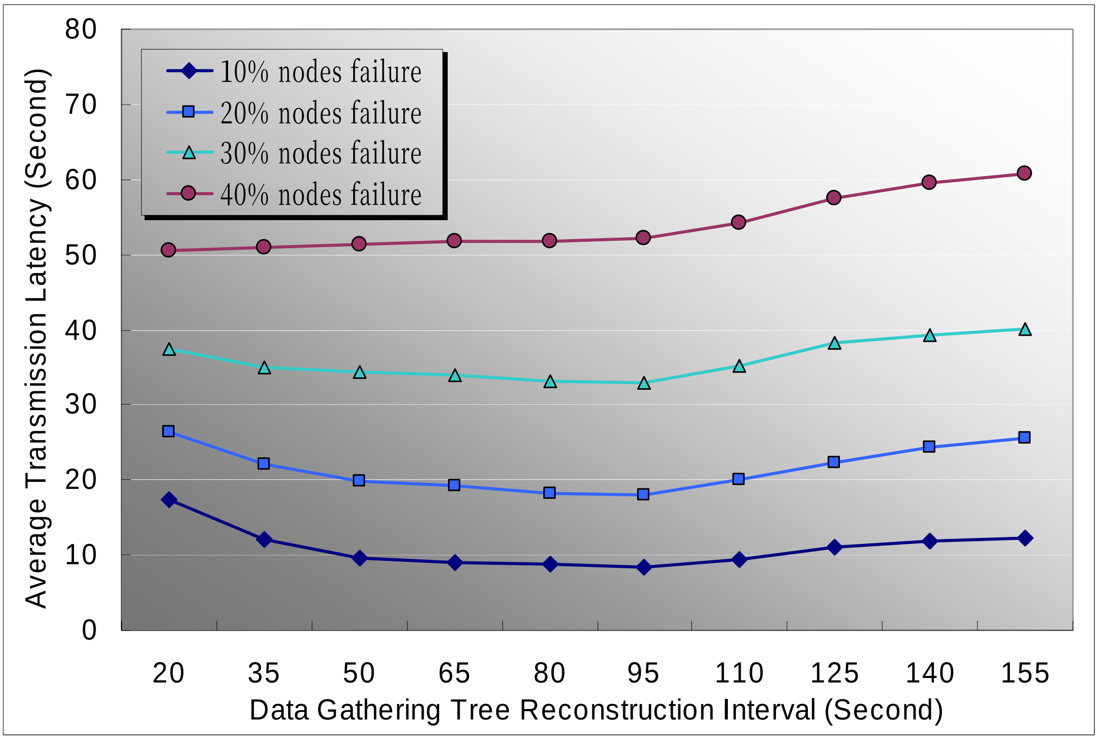

Figure 3-6： The overhead of transmission latency caused by reconstruction

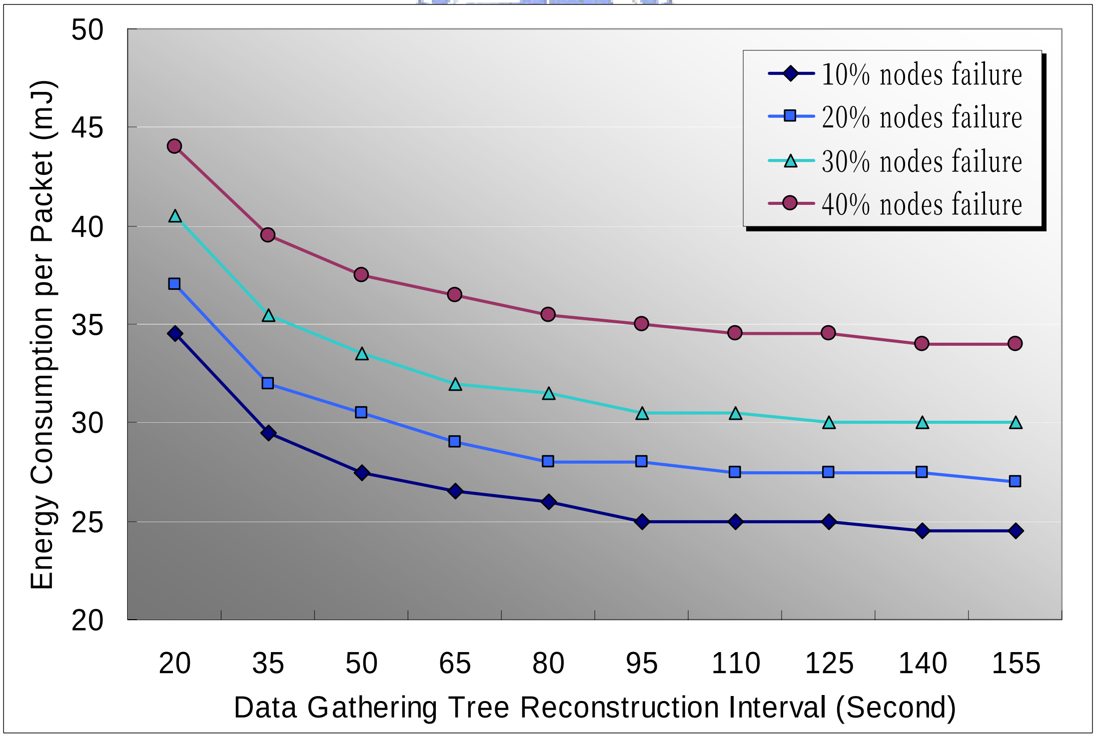

Figure 3-7： The overhead of energy caused by reconstruction

However, some applications require critical real-time data transmission. The 95 seconds interval is still too long for these applications. Thus, we introduce a temporal path mechanism to adapt these applications. Take advantage of the “upper layer list”, each sensor node is able to know which one level higher node can be accessed by it. By temporal path mechanism, sensor node will regard its parent node to be failure when it fails to receive the ACK message three times. As long as a sensor node regards its parent node to be failure, it will randomly choose one node from its “upper layer list” to be its temporal parent and transmit data packets to this temporal parent until next data gathering tree reconstruction. This mechanism can help nodes to reconstruct their paths between each tree reconstruction. However, this mechanism can not find the best parent node for each sensor node. Thus, the data gathering tree reconstruction is still needed because it can build the better data gathering tree.

3.2.5 Overhearing Avoidance

In most wireless networks, wireless devices always keep radio on to listen to all data transmissions. In 802.11 CSMA, this overhearing is used to perform effective virtual carrier sense. As a result, each node overhears many packets which are not assigned to it. This causes a significant energy waste, especially in dense and heavy traffic networks.

Figure 3-8 shows a multi-hop network which is formed by seven sensor nodes and a base station. The data flow in this network is from node A to base station. Each node can only hear the transmission from its immediate neighbors. For example, node D can hear the transmission form node C and E. But node D can not hear the transmission from node F to E or B to C. The dotted lines denote the interference areas of each sensor nodes. Suppose node D is currently transmitting a data packet to

E. The CTS packet from node E would be heard by node F and the RTS packet from node D would be heard by node C. Thus node F should go to sleep since its transmission interferes with E's reception. Node C should also go to sleep because its reception would be interfered by node D's transmission. This means node B can not transmit any packet to node C. In the network, only node A and node G can still work now. This illustrates a conclusion that if a node is in transmission, the nearest nodes able to transmit must be at least three hops away. The sensor nodes which are one or two hops away should go to sleep to save energy. This is a quite important conclusion that affects the design of LAMAC.

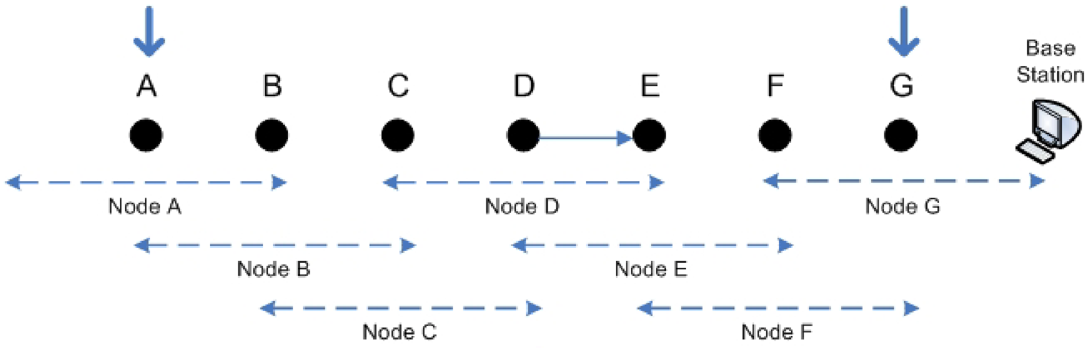

Figure 3-8： A multi-hop network and interference range of each node

3.2 Adaptive Sleeping

The scheme of periodically listen and sleep is able to reduce the energy and time spent greatly on idle listening. However, when a sensed packet generated, it is desirable that the sensed data can be transmitted through the network without too much delay. When each node strictly follows its active-sleep schedule, there is a potential delay on each hop. And the average value is proportional to the length of the frame. We therefore introduce a technique called adaptive sleeping to reduce transmission latency and use active-sleep cycle more flexible and efficiently.

3.3.1 The latency of multiple data forwarding

As long as MAC protocol use sleep-active cycle schedule, the sleeping latency will happen. For example, the most critical latency in S-MAC is the sleeping latency. Sleeping latency is the most serious delay among all kinds of transmission latency. And it also exists in LAMAC. We use an example to illustrate the sleeping latency in our proposed protocol. Figure 3-9(a) shows a multi-hop chain network. In this network, data flow is from node A to node D. Figure 3-9(b) and 3-9(c) show the time relationship and packet forwarding condition among all sensor nodes. As shown in Figure 3-9(b), only one packet is transmitted through the network. Because of the stair-like schedule, this packet goes through the network without sleeping latency. The transmission duration of this packet is shown in below of Figure 3-9(b). This is an ideal case and only happens in networks whose traffic is very light. Figure 3-9(c) shows a network with average traffic. Node A gets two packets to transmit. The first packet is transmitted without sleep latency. But node A is not able to transmit the second packet until next sending slot. This is because one sending slot is only long enough to transmit one packet. The whole transmission duration is shown in Figure 3-9(c) below. This duration is much longer than that of Figure 3-9(b) because of the sleep period. As long as a node has more than one packet to transmit, it needs many sending slots to handle all packets. Once a node waits for another sending slot, sleeping latency happens. The sleeping latency will significantly reduce throughput and increase the overall transmission latency. We therefore introduce a mechanism to switch the nodes from the low-active-cycle mode to a more active mode in this case.

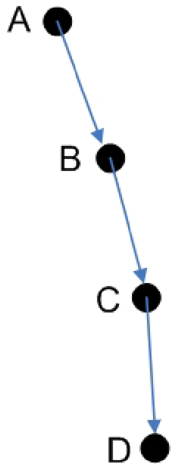

Figure 3-9(a)：A multi-hop chain network

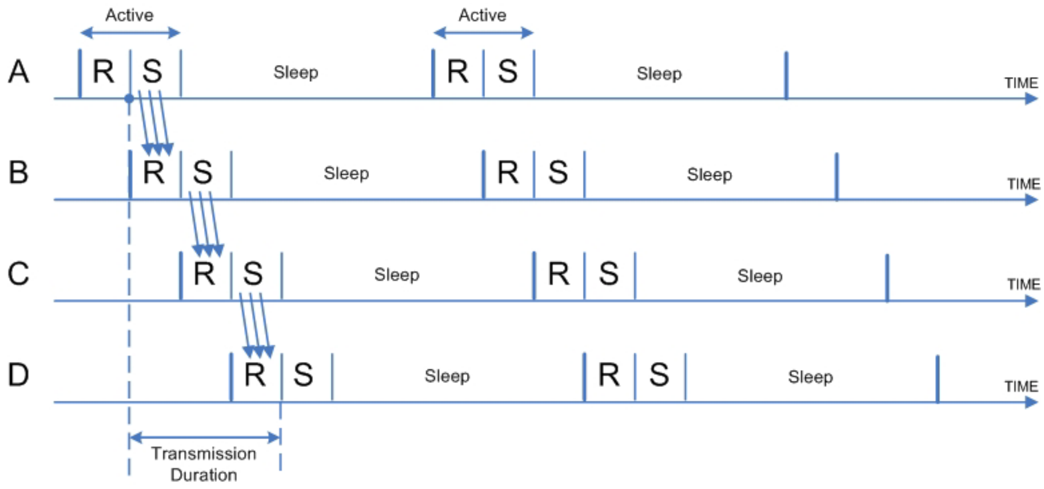

Figure 3-9 (b)：Forwarding condition with one packet to

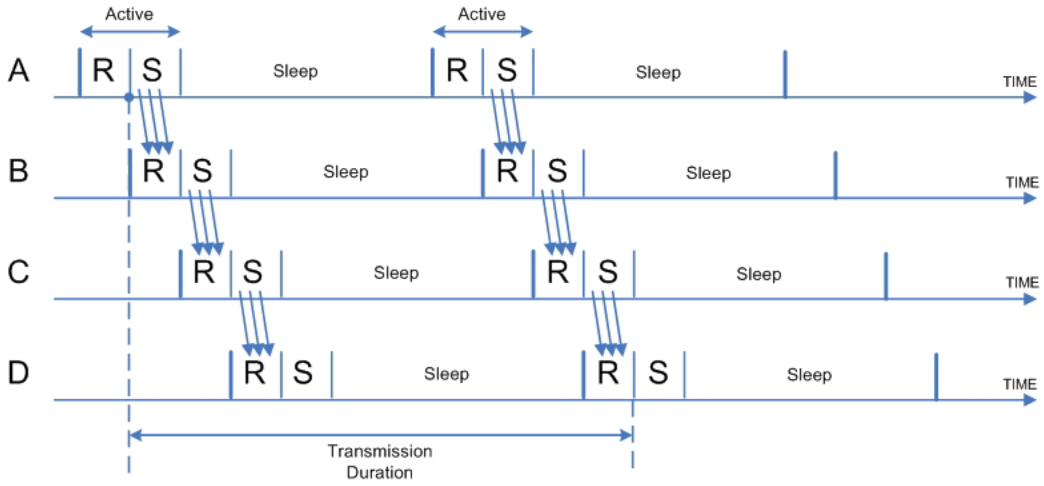

Figure 3-9 (c)：Forwarding condition with two packet to

Figure 3-9： An example of sleeping latency

3.3.2 Adaptive Sleeping Scheme

We propose an important technique, called adaptive sleeping, to reduce the transmission latency caused by the periodic sleep of each node in a multi-hop network. The basic idea is to let receiver know that there are some packets for it but remaining active time is not long enough to transmit these packets. It works as follows： if a node gets more than one packet to transmit, it will set the future-request-to-send （FRTS） flag of these packets except the last packet. The receiver will hold another extra active period during sleep period for these packets. We call the extra active period ”adaptive active period”. Figure 3-10 shows an example of adaptive sleeping. Node A has two packets to transmit to node B. In the original active period, node A transmits the first packet to node B. The FRTS flag of the first packet is set. Node B knows node A has more packets for itself by the FRTS flag. Thus node B holds an adaptive active period which is indicated by dotted line. Node A will use the adaptive active period to transmit the second packet. Having no other packets to send, node A clears the FRTS flag in the second packet. After transmitting the second packet, node A and B both go to sleep until next original active period. If there are more packets to send, node A can set the FRTS flag again. And node B will hold another adaptive active period for these packets. The advantage of using adaptive sleeping technique is that the active-sleep cycle can be used more flexible and be adaptive to different traffic load. Without using adaptive sleeping, sensor nodes need to wait until the beginning of next fame to transmit the second packet. This sleeping latency greatly increases the overall transmission latency and decreases throughput of the whole system. However, by using adaptive sleeping, sensor nodes can switch the low-duty-cycle mode to a more active mode if necessary. This capability can not only reduce transmission latency but also make LAMAC more adaptive to different traffic load.

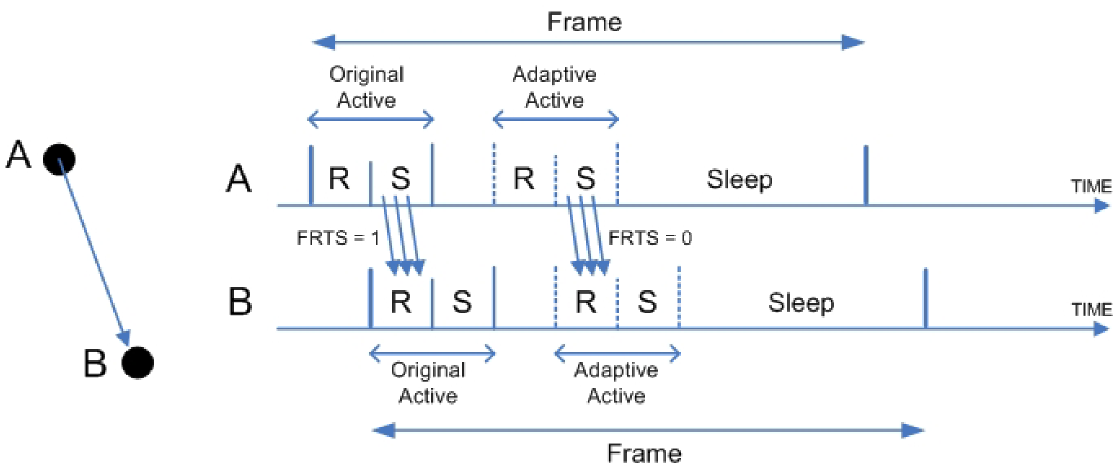

Figure 3-10： An example of adaptive sleeping

As mentioned earlier, a node which is currently transmitting packets, the nearest nodes which are able to work must be at least three hops away. This is because the transmissions of packets that are one or two hops away interfere with the current transmission. In Figure 3-11, if node B decides to hold an adaptive active period, it must wait S interval for the current packet to transmit to nodes D which is three hops away from node A. The timing diagram is shown in Figure 3-11. In order to simplify the diagram, only sending slots remain in the figure. There is time slot axis in Figure 3-11 below. We use a sending slot to be one unit of time. In time slot 2, node A transmits a packet to node B. According to our stair-like active schedule, this packet is transmitted to node C in time slot 3 and to node D in time slot 4. Node D is three hops away from node A, the transmission between node D and E will not interfere with the transmission between node A and B. Thus node B can hold an adaptive active period in time slot 5 and receive the second packet from node A. It means if a node wants to hold an adaptive active period, it must wait an S interval of two sending slots to avoid the collision. We let nodes go to sleep to save energy between original active period end and adaptive active period start.

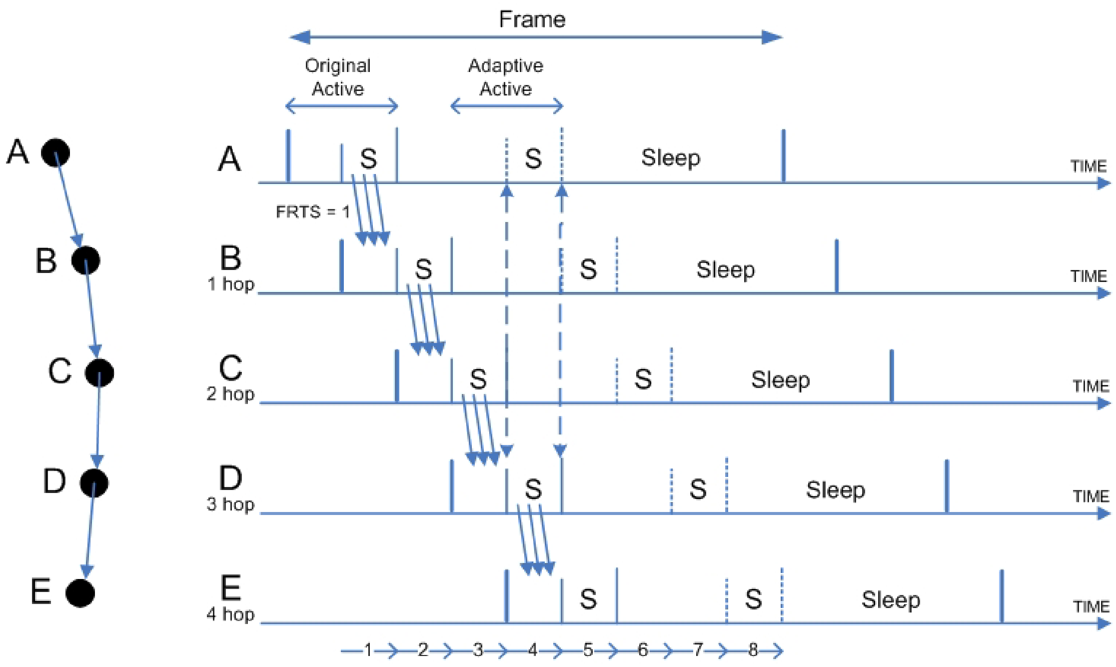

Figure 3-11： Time relationship between two active periods

Once the FRTS flag is set, this flag will not be clear by any nodes. This means every node which receives this packet will hold an adaptive active period. Figure 3-11 shows the mechanism. Node A set the FRTS flag of the first packet. And then this packet will be transmitted through the chain network. Every node will hold an adaptive active period after two sending slot. This makes the second packet transmitted through the path without sleeping latency.

But even we use the adaptive sleeping technique, sleeping latency still happens in some special cases. Figure 3-12 shows an example. Both node B and node C have packet to transmit to node A at the same time. Node B wins the communication medium and transmits its packet to node A. Because of having only one packet to transmit, node B doesn’t set the FRTS flag of its packet. Thus node A will not hold an adaptive active period for further packets. Node C must wait until next send slot to transmit its packet and suffer sleep latency. It is impossible for node B to set the FRTS flag for other sensor nodes because node B never knows whether or not other nodes have packets to send. Therefore, we introduce a mechanism to enhance the adaptive sleeping technique for this case.

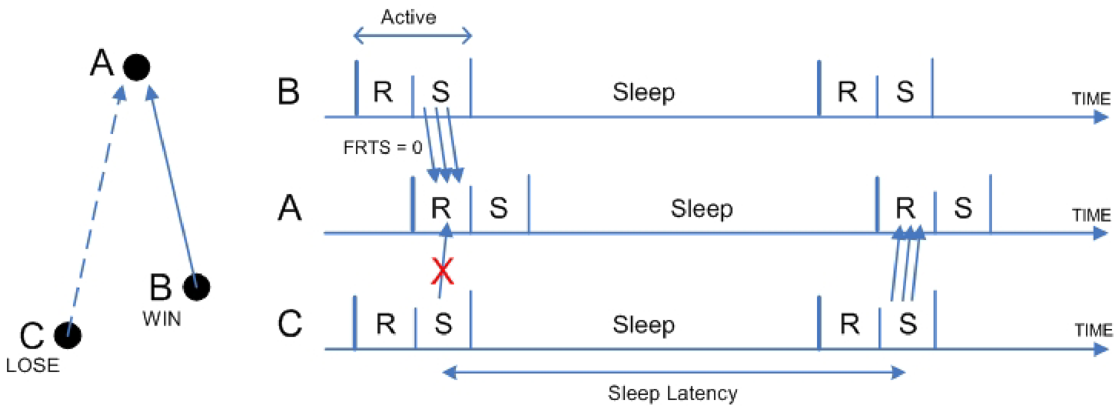

Figure 3-12： Sleeping Latency caused by contention mechanism

We propose a mechanism, called future request-to-send packet (FRP), to reduce the latency caused by contention mechanism. The basic idea is to let receiver know that we still have packets for it, but are ourselves prohibited from using the medium. In this way, if a node loses the communication medium in contention, it will immediately send a future-request-to-send (FRP) packet to its receiver. The FRP packet is very small and only contains the receiver’s ID. Sender’s ID is unnecessary because this packet is used for receiver to hold an adaptive active period. Figure 3-13 shows a similar example to Figure 3-12. Node B and node C contend for the medium and node B wins the contention. As long as node C knows itself loses the medium, it immediately sends a FRP packet to node A. After receiving this FRP packet, node A knows that there are other packets for it. Thus node A will hold an adaptive active period after S interval. The adaptive active period is indicated by dotted line in Figure 3-13. Then node C can use the extra active period to transmit its packet. This mechanism is similar to the function of FRTS flag. By using this mechanism, the sleep latency will significantly be reduced.

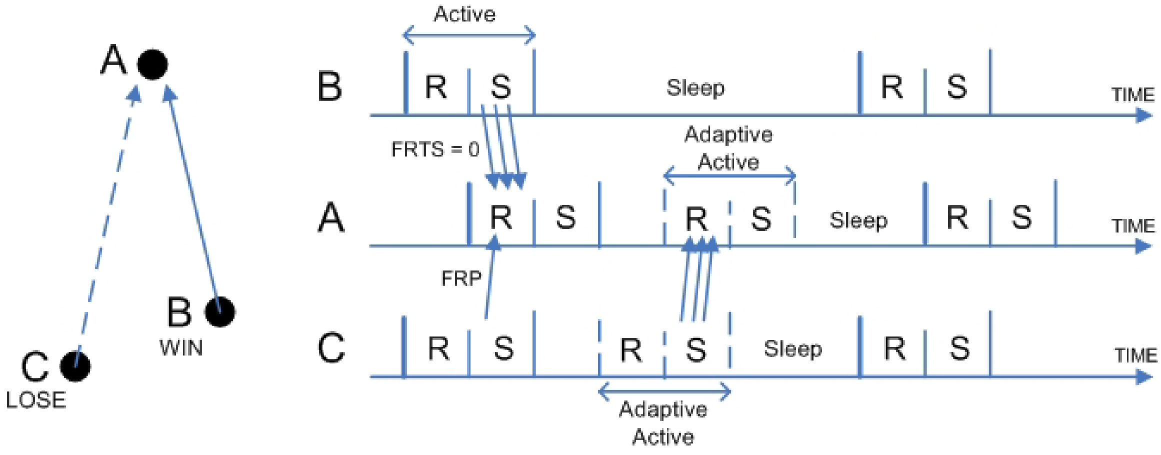

Figure 3-13： An example of FRP mechanism

Once a node receives the FRP packet, it must pass this packet to next hop node. By this way, the extra active period will propagate along the forwarding path. In addition to reducing sleep latency, the throughput of the network will increase.

For the FRP solution to work, the length of active period must be increased slightly. Since the FRP packet is quite small, the increasing value is also small. Compared with the improvement of the throughput and latency, we believe it is worthwhile to use this mechanism.

4. Latency Analysis

When a packet transmits through a multi-hop chain network, it will suffer many difference kinds of delay. The total delay which a packet encounters is called the transmission latency. We will analyze the transmission latency in the following section. The latency in both LAMAC and S-MAC will be analyzed together. And the performance will be compared in the section.

When a packet transmits through a multi-hop network, it will encounter the following delays：

Contention Delay：Contention delay happens when the sender performs carrier sense. After carrier sensing, the interval for sender and receiver to exchange control packet such as RTS, CTS is included in the contention delay. In some MAC protocols, sender will stay in idle mode when senses some other transmission. This is named back-off delay and is also included in the contention delay. Basically, the contention delay is determined by the contention window size and control packet exchanging interval.

Transmission Delay： The transmission delay is the time between the start and the end of a transmission. The transmission delay is determined by the channel bandwidth and packet length. When the packet length increases, the transmission delay also increases.

Propagation Delay： The propagation delay is determined by the distance between the sender and receiver. When the distance between the two nodes is quite long, the propagation delay will be a serious problem. However, node distance is normally very small in wireless sensor networks. Thus the propagation delay is often be neglected.

Processing Delay： Processing delay refers to the time a node needs to process the packet before forwarding it to the next hop. This delay mainly depends on the computing power of the node. In wireless sensor networks, the sensor nodes often do not need to process packets but forward packets to its next hop. Hence the processing delay is quite short.

Queuing Delay： Queuing delays happens when the traffic load is heavy. When the traffic becomes heavy, the queuing delay is often the dominant factor of transmission.

Sleeping Delay： In order to get good energy efficiency, some MAC protocols introduce the active-sleep schedule to the radio. When a sender gets a packet to transmit, it must wait until its receiver wakes up. The delay is also called sleeping latency and is often determined by the frame length of its active-sleep schedule.

We analyze the transmission latency of different MAC protocols in a simple case which the traffic is very light, e.g., only one packet is moving through the network, so that there is no queuing delay. We further assume that the propagation delay and the processing delay can be ignored. We only take contention delay, transmission delay, and sleeping latency into account.

Supposed a packet will be transmitted through N hops from source node to base station. By observing the transmission mechanism, we can know that the contention mechanism is immediately followed by the packet transmission. Thus we combine the contention delay and transmission delay to be the CT delay in our analysis and denote its value at hop n by $t_{ct,n}$. Its actual value is determined by different MAC protocol. In LAMAC, its value is equal to the length of sending or receiving period. And in S-MAC, its value is equal to the length of listen slot plus the transmission time of one packet. The value is fixed in both LAMAC and S-MAC because of the fixed length of packets and contention interval.

We first look at the MAC protocol without sleeping such as 802.11 CSMA. When a node gets a packet, it immediately starts contention mechanism and tries to forward it to the next hop. The average delay at hop is $t_{ct,n.}$. The entire latency over N hops is：

$$Delay(N) = \sum_{n=1}^{N} t_{ct,n} \tag{1}$$

Because the length of CT delay is the same at each hop, by change $t_{ct,n}$ to the fixed values T_{ct}, we can summarize the value to：

$$Delay(N) = NT_{CT} \tag{2}$$

Equation (2) shows the transmission latency will increase linearly with the length of hops in the MAC protocol without sleeping.

Now we look at LAMAC, which introduces a sleeping latency at each hop. The sleeping latency is denoted by $t_{s,n}$ for the nth hop. In order to reflect a very low duty cycle, we set the sending period to $<=$ 10% length of a frame. And a frame length is denoted by T_f which is assume to be much larger than $t_{ct,n}$.

The delay at hop n is：

$$D_n = t_{s,n} + t_{ct,n} \tag{3}$$

However, if the node is not the source node which generates the packet, it does not have sleeping latency in LANAC. This is because the sending slot follows immediately the receiving slot in LAMAC. Once an intermediate node gets a packet, it can forward this packet to next hop immediately without sleeping latency. Thus if a node is not the source node, its delay equation must change to：

$$D_n = t_{ct,n} \tag{4}$$

The delay of source node is denoted by D_1 and its equation is：

$$D_1 = t_{s,1} + t_{ct,1} \tag{5}$$

Because a packet can be generated on the source node at any time within a frame, the sleeping latency on the first hop, $t_{s,1}$, is a random value which lies in （0, T_f）. And its mean value is $T_f/2$.

Combining the delay on the first hop node and other nodes, we can get the overall delay of a packet over N hops network as：

$$\begin{aligned} Delay(N) &= D_1 + \sum_{n=2}^{N} D_n \\ &= t_{s,1} + t_{ct,1} + \sum_{n=2}^{N} t_{ct,n} \\ &= t_{s,1} + \sum_{n=1}^{N} t_{ct,n} \\ &= \frac{1}{2}T_f + NT_{CT} \end{aligned} \tag{6}$$

We assume $T_f = k\,T_{ct}$. So equation (6) becomes：

$$Delay(N) = \frac{N}{K}T_f + \frac{1}{2}T_f \tag{7}$$

Equation (7) shows that the multi-hop transmission latency linearly increases with the number of hops in LAMAC. The slope of the line is the T_f/k. Compared with (2), although we introduce the sleeping schedule into LAMAC, the transmission latency only increase $T_f/2$

Now we look at the transmission latency in S-MAC. S-MAC can only forward packet one hop in one frame. The delay at hop n is the same as(3)

In S-MAC, contention mechanism only starts at the beginning of each frame. After a node gets a packet in a frame, it has to wait until the next-hop node to wake up. This means it must wait to the beginning of the next frame. This indicates：

$$T_f = t_{ct,n-1} + t_{s,n} \tag{8}$$

Substituting $t_{s,n}$ into equation (3), we obtain：

$$D_n = T_f + t_{ct,n} - t_{ct,n-1} \tag{9}$$

There is an exception on the first hop. As mentioned earlier, a packet can be generated at any time. Thus the delay on the first hop is the same as (5)

Combining the equation (5) and (9), we can derive the overall transmission latency in S-MAC as：

$$\begin{aligned} Delay(N) &= D_1 + \sum_{n=2}^{N} D_n \\ &= t_{s,1} + t_{ct,1} + \sum_{n=2}^{N} \left(T_f + t_{ct,n} - t_{ct,n} \right) \qquad (10) \\ &= t_{s,1} + (N-1)T_f + t_{ct,N} \end{aligned}$$

Because that the $t_{s,1}$ is equal to $T_f/2$, $T_f = k T_{ct}$, and $t_{ct,N} = T_{ct.}$ Equation (10) becomes

$$\begin{aligned} Delay(N) &= NT_f - \frac{1}{2}T_f + \frac{1}{K}T_f \\ &= NT_f - \frac{K-2}{2K}T_f \end{aligned} \tag{11}$$

Equation (11) shows the transmission latency in S-MAC. The slope of the line is the frame length T_f. Because we introduce a very low duty cycle, the value of k is at least 10. Compared the overall latency equation of S-MAC with ours, S-MAC gets much transmission delay according to the sleeping latency.

In order to reduce latency, S-MAC uses a technique called adaptive active. The basic idea is to let the node who overhears its neighbor's transmissions (RTS or CTS) wake up for a short period of time at the end of the transmission. If the node is the next-hop node, its previous hop node is able to pass the data to it immediately instead of waiting for the next frame. If the node does not receive anything during the adaptive listening, it will go back to sleep until its next scheduled listen time. An example is shown in Figure 4-1. In Figure 4-1, node A is currently transmitting a packet to node B. Every node in the transmission range of node A and node B will wake up in the end of the current transmission. The transmission range of node A and B is denoted by the two blue circles in this figure. Node C is in the transmission range of node B and will wake up for the adaptive active. Thus node B is able to transmission the packet to node C when it receives the whole packet from node A. However, the next hop of node C, which is node D, is out of the transmission range of node A and node B. Node D will not perform adaptive active. Hence node C has to wait until the beginning of next hop to transmit this packet to node D. This causes a sleeping latency.

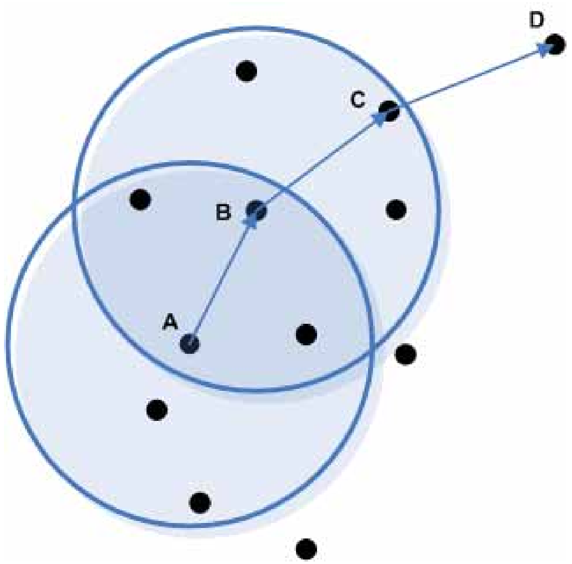

Figure 4-1： Adaptive active scheme of S-MAC

The transmission latency of S-MAC with adaptive active is also be analyzed. The latency equation is

$$\begin{aligned} Delay(N) &= \frac{N}{2}T_f - \frac{1}{2}T_f + 2T_{CT} \\ &= \frac{N}{2}T_f + \frac{4-K}{2K}T_f \end{aligned} \qquad (12)$$

We can see that the average latency in S-MAC with adaptive active still linearly increases with the number of hops. Now the slope of the line is $T_f/2$. Compared with that of no adaptive active (11), it is reduced by half. However, it is still much larger than the transmission latency of LAMAC

Figure 4-2 shows the simulation results of transmission latency with different hop length. Besides LAMAC and S-MAC, we also evaluate the full active MAC protocol, 802.11 CSMA, to show the least transmission latency. As the analyzed delay equation, the latency of each MAC protocol increases with the number of hop counts. S-MAC without adaptive active has the largest latency. S-MAC with adaptive active also has much higher latency than LAMAC and 802.11 CSMA. This is because S-MAC suffers sleeping latency in each hop. By using adaptive active, S-MAC can transmit a packet two hops in a frame. However, the packet stops at the third hop. The result is the same with Equation (12). LAMAC has a slight higher latency than 802.11 CSMA. As mentioned earlier, this extra latency is caused by the random generating time of packet at the source nodes and its mean value is half of a frame length. Although LAMAC will suffer sleeping latency at the source node, the transmission efficiency is much better than S-MAC.

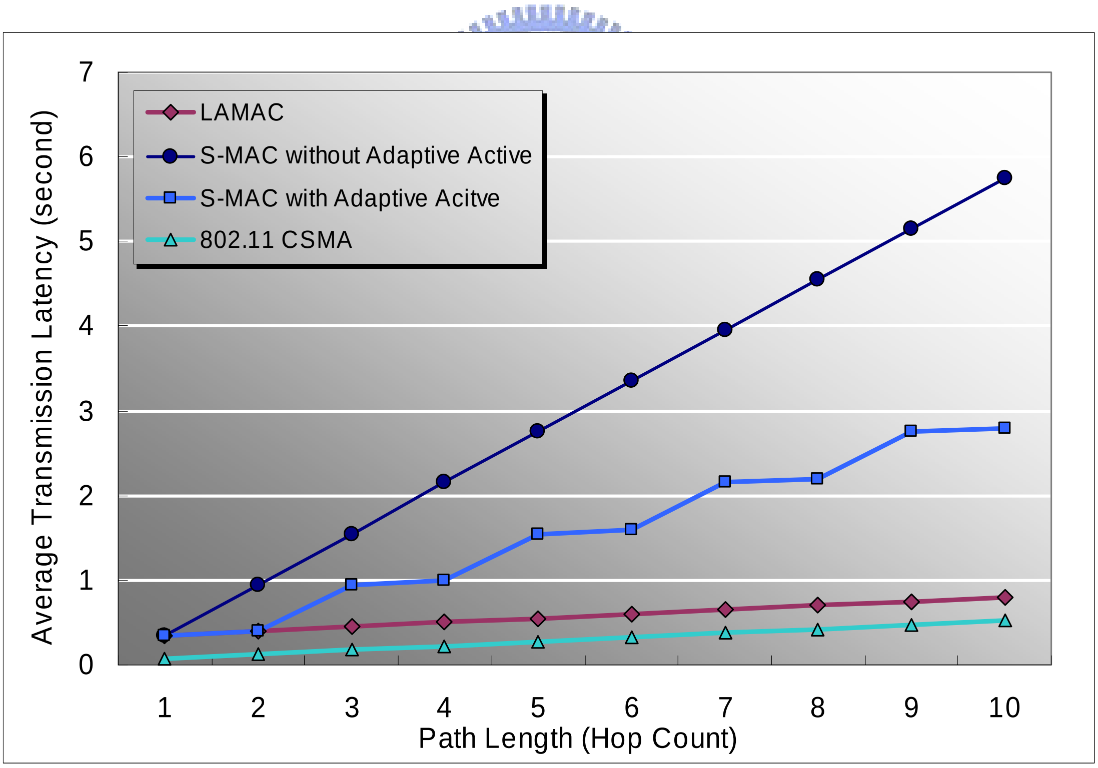

Figure 4-2： Average transmission latency with different path length

Figure 4-3 shows the transmission latency with different duty cycle. Duty cycle refers to the ratio of active period within a frame. If duty cycle is 1/12, it means a frame is 12 times the length of active period. In our simulation, the duty cycle is from 1/6 to 1/33. As Figure 4-3 shows, S-MAC without adaptive active has the largest latency. The result shows that the lower the duty cycle, the larger the difference between LAMAC and S-MAC. 802.11 CSMA also has slight lower latency than LAMAC.

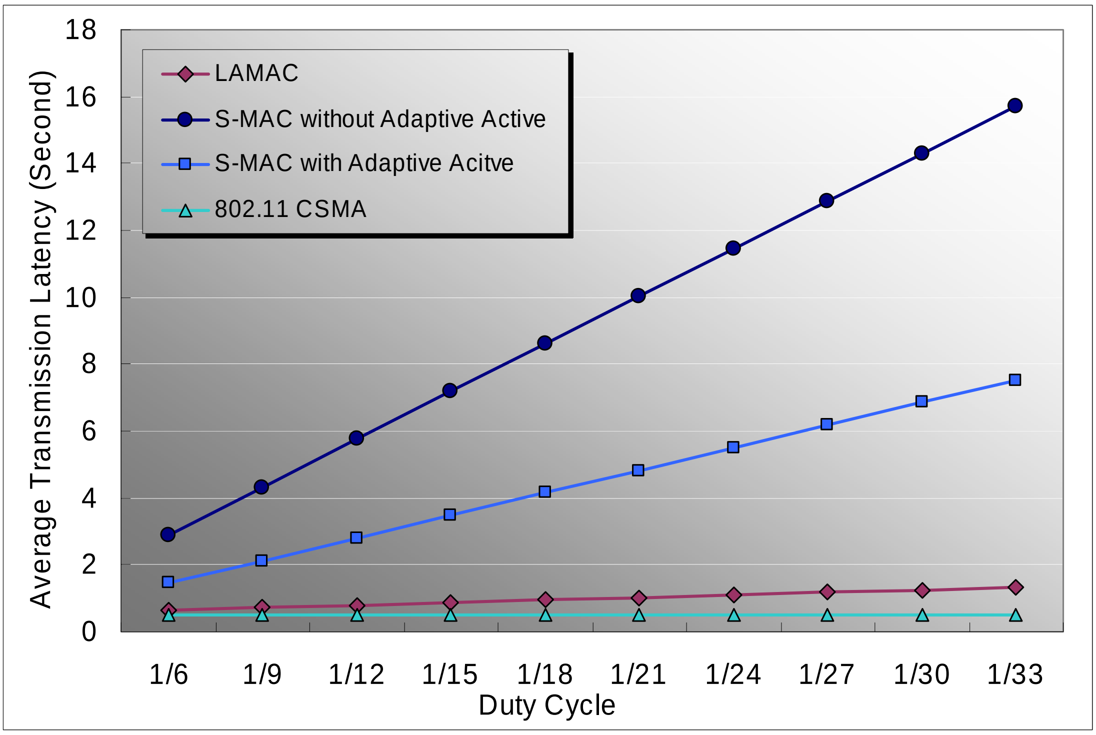

Figure 4-3： Average transmission latency with different duty cycle

5. Performance Evaluation

In the following section, we use two different kinds of network as our experimentation environment. The goal is to show the performance of energy, latency, and throughput of our proposed LAMAC protocol. As a comparison, we measured the performance of other MAC protocols including S-MAC and 802.11 CSMA. We use 802.11 CSMA as a MAC protocol without sleeping. Thus it has the optimal throughput and the least transmission latency. However, it has no energy saving features at all. We implement S-MAC both with and without adaptive active. To facilitate the measurement of multiple messages traveling through a multi-hop network, a message queue is added at the application layer to buffer the outgoing message on each node.

There are four ways we use to evaluate performance. They are transmission latency, energy consumption, throughput, and protocol work efficiency. Transmission latency refers to the transmission efficiency of MAC protocol and is the most important part in our evaluation. We let each packet have its own timer. When a packet is generated, it set its timer to 0. When the packet arrive base station, it stops its timer and uses the final time as its transmission latency.

Energy consumption is evaluated to reflect the energy efficiency. This is quite important in designing MAC protocol of wireless sensor network. Instead of measuring energy consumption on each sensor node, we measure average energy consumption of the whole network to transmit a packet. We think the measurement of energy consumption on each node is meaningless. For example：If a MAC protocol always put sensor nodes into sleeping mode. After running a certain time, the network definitely consumes very few energy. This looks like the MAC protocol gets quite good energy efficiency. However, there are almost no packets arrive base station. This design is meaningless. Thus we measure energy consumption per packet instead of sensor node.

Throughput indicates the amount of data received of base station in a certain time. Generally, throughput is highly relative to the traffic load. However, due to some improper design of MAC protocol, throughput may not have the same ratio of increasing with traffic load. Thus, throughput can be regarded as an way to evaluate MAC protocols.

The definition of work efficiency is the amount of data which can be received by base station before the system shut down. System shut down means the level-1 sensor nodes all exhaust their energy. The base station can not receive any more packets. The work efficiency is the measurement of the amount of data received by base station before system shut down. The more the amount of data received before system shut down means the MAC protocol can use energy more effectively.

5.3 Simulation setup

We have built a realistic model of the MICA mote, developed at UCB. The MICA motes have the Atmel ATmega128L microcontroller with 128 kB of flash and 4 kB of data memory. Mica motes are equipped with the RFM TR3000 radio transceiver and a matched whip antenna. It provides a transmission rate of 19.2Kbps and has three working modes, i.e., receiving mode, transmission mode, and sleep mode. The power consumptions of the radio in receiving, transmitting, and sleep modes are 14.4 mW, 36 mW, and 0.015mW, respectively [28].

In our experiment, only three kinds of packets are used. They are control packets (e.g.: RTS, CTS packets), data packets, and FRP packets. In our implementation, the header, payload and CRC fields have 6Bytes, 90Bytes, and 2Bytes. Control packets only have 6 bytes header and 2 bytes CRC fields. Data packets are about 98 bytes. FRP packets only contain receiver's ID. Thus the length of FRP packets is 2 bytes.

In our experiment, we evaluate LAMAC with a sending period of 60mS which is tuned for maximum traffic load. And the listening slot of S-MAC is set to 90mS. The duty cycle is from 3% to 15%. Thus a frame length is from 720mS to 3.9S for LAMAC and 540mS to 3S for S-MAC. Some important parameters of our experiment are listed in Table I.

Radio Bandwidth	19.2 Kbps
Control Packet Length	8 Bytes
Data Packet Length	98 Bytes
FRP Packet	2 Bytes
Transmit Power	36 mW
Receive Power	14.4 mW
Sleep Power	0.015mW
Duty Cycle	3% ~ 15%

Table I： Some parameters of our evaluation

5.3 Evaluation on a multi-hop chain network

The first scenario we use to evaluate is a multi-hop chain network. This is a simple network which contains only 10 sensor nodes and a base station to collect data packets. The chain network is shown in Figure 5-1. Each node in the network can only hear the radio signal of the immediate neighbor nodes. The first node is source node which generates data packets. These data packets move through the chain network to base station.

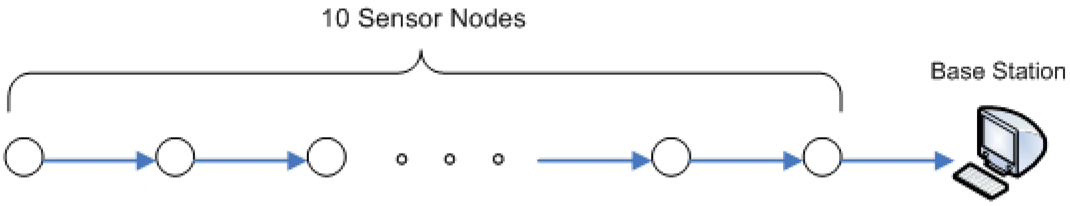

Figure 5-1： A multi-hop chain network with 10 sensor nodes

In this experiment, four MAC protocols including LANAC, S-MAC without adaptive active, S-MAC with adaptive active, and 802.11 CSMA will be implemented. We will evaluate the protocol under different traffic load. We change the traffic load by varying the inter-arrival period of packets. The inter-arrival of packets varies from 1 S to 5.5 S. If the packet inter-arrival period is 5 S, a packet is generated every 5 S by source node. 1-S inter-arrival packet interval stands for the highest traffic load because the wireless channel is nearly fully utilized by using this interval. All packets may be queued at each sensor node for transmission. Thus the queuing delay will significantly increase the transmission latency. 5.5-S inter-arrival packet interval expresses the lightest traffic load network. In this traffic, there is no queuing delay on each sensor node. The extra latency is only caused by sleeping latency. For each traffic pattern, we have done 1000 independent tests by using different MAC protocols in order to get accurate result.

In each test, the source node periodically generates 100 packets and passes these packets to base station. We set the duty cycle to 8.5% and a frame length to 1.2 S. This is an average value in our experiment. We measure the transmission latency of each packet and energy consumption of radio on each sensor node. The actual time to finish the transmission is different for each MAC protocol and packet interval.

Figure 5-2 shows the transmission latency per packet with different packet generation interval. In all MAC protocols, the latency decreases with the increasing of data interval. However, in the 1-S inter-arrival packet interval, the highest traffic load, S-MAC has much higher transmission latency than LAMAC. This is because S-MAC does not use the transmission schedule efficiently. It wastes a lot of time by putting sensor nodes into sleeping mode. In the sleeping period, the whole network stops transmission and each packet has to be queued on sensor node. Whenever a packet generated, it has to wait for a long time to transmit. According to the 1.2-S frame length, only one packet can be transmitted from the source node every 1.2 S. But the packet generation interval is 1 S. It means a new packet has to wait for the previous packet to transmit on the source node. And on each intermediate node, it still suffers queuing delay for waiting the order packet to move. However, LAMAC can transmit packet very efficiently. By using adaptive sleeping scheme, LAMAC can transmit packets as soon as possible. LAMAC suffers queuing delay only in the 1-S inter-arrival packet interval case. This is because whenever a packet generated, it must wait for the next frame to send. As long as a packet leaves the source node, it will be transmitted sequentially and quickly through the network because of the continuous sending period on each sensor node. These are no queuing delay on sensor node except the source node. 802.11 CSMA has slight better performance than ours because it has no sleeping period. Whenever a packet is generated, it will be transmitted to the next hop immediately.

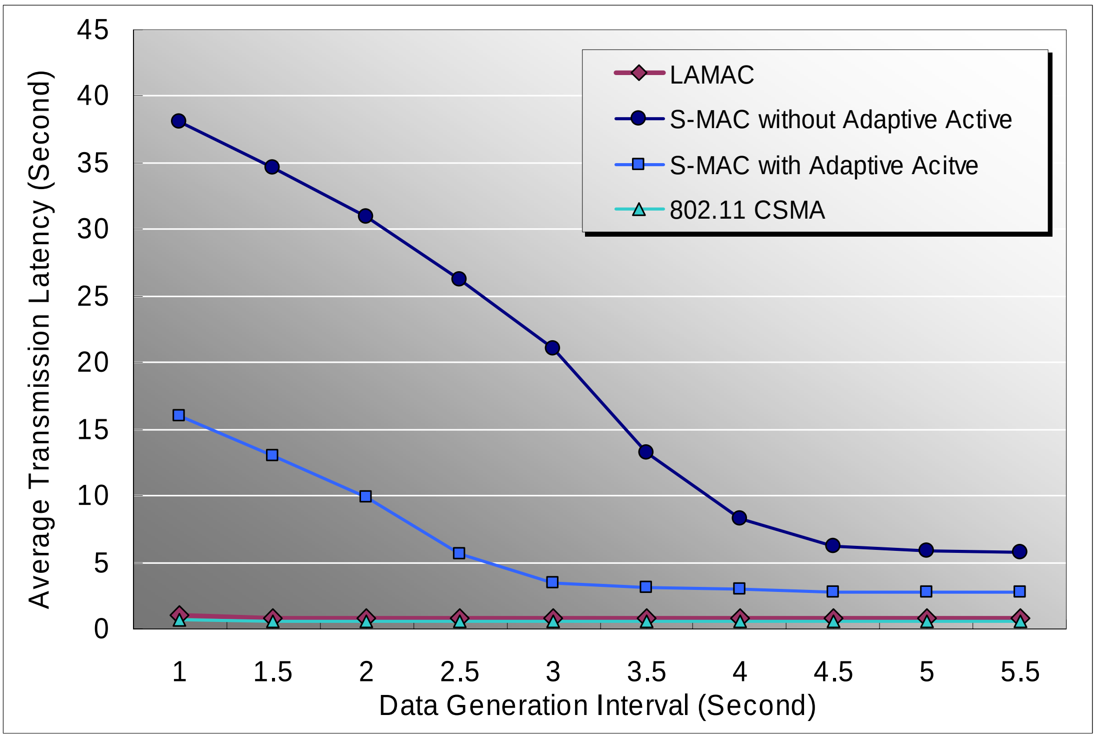

Figure 5-2： Average transmission latency under different traffic load

Figure 5-3 shows the measured average energy consumption per packet. 802.11 CSMA wastes much more energy than LAMAC and S-MAC because of idle listening problem. The longer the data generation interval, the more the energy wastes in idle listening. Idle listening problem can be reduced by putting nodes into periodic sleeping. Thus LAMAC and S-MAC can save much more energy than 802.11 CSMA. In the highest traffic load of 1-S inter-arrival packet interval, 802.11 CSMA uses more than 7 times the energy used by LAMAC. In the lightest traffic load, we even outperform 21 times than 802.11 CSMA. Compared with the performance of S-MAC, we also get twice to triple energy saving than it. This is because LAMAC transmit packet in an efficient way. In most cases, only the sender and receiver will awake up in the packet transmission. After a packet transmission completes, each node may wake up only 2 times, one for receiving and the other for transmitting. In S-MAC, each frame can only forward one packet to move one hop without adaptive active or two hop with adaptive active. Thus after a packet transmission completes, each node may wake up several times. And most times, sensor nodes have no packet to send and waste energy in idle listening. In other words, we reduce more idle listening energy wastage than S-MAC. We can observe that when idle listening dominates the total energy consumption, the periodically sleep plays a key role for energy savings.

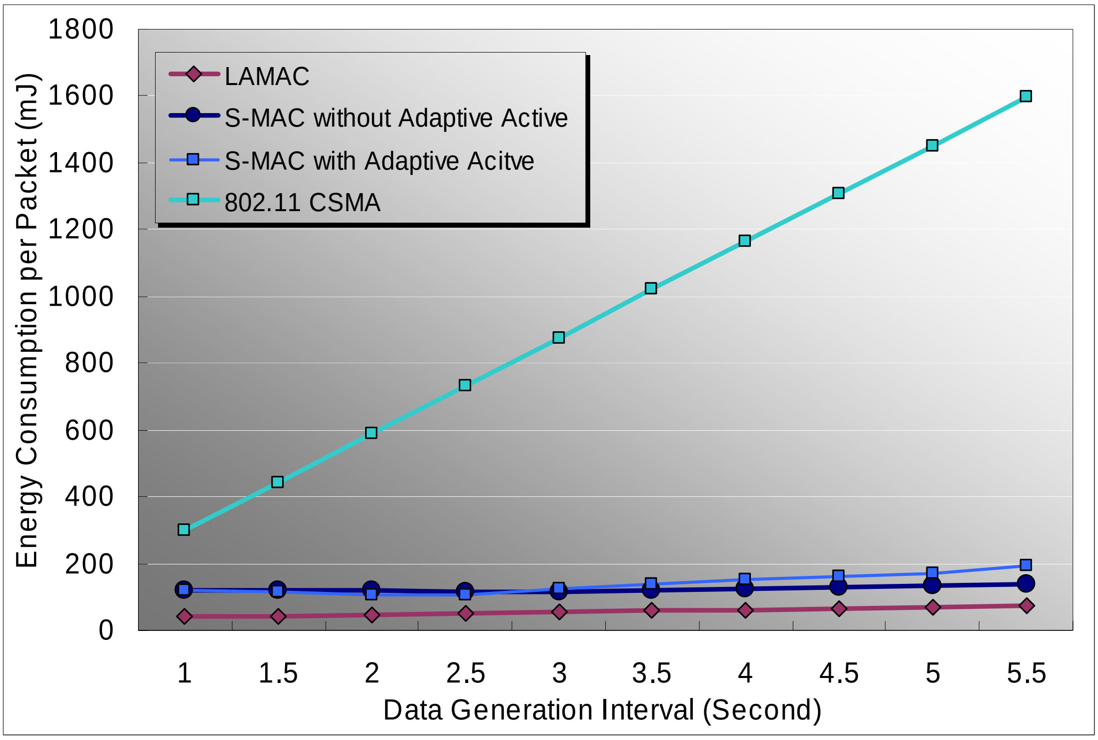

Figure 5-3： Energy consumption per packet under different traffic load

In the last evaluation on this multi-hop chain network, we will evaluate the throughput. Throughput refers to the amount of data which are received by base station in a unit time. In our experiment, we measure throughput in one second. That means we will evaluate the average amount of data received by base station in one second. The result does not count any control packets. Only data packets received by base station are counted for the throughput.

We expect that there are always data packets over all ten hops in the highest traffic load. If contention mechanism is not designed properly, contention which happens at each hop will significantly reduce throughput.

Figure 5-4 shows the throughput of all MAC protocols with different packet generation interval. The result proves our expectation. Although in heavy traffic load such as 1-S inter-arrival packet interval, the throughput of S-MAC is still very low because of its improper contention mechanism. In the highest traffic load, S-MAC with adaptive active and without adaptive active only achieve about 1/4 and 1/7 of the throughput compared with LAMAC. The result also shows that all throughputs reduce as traffic load decreases. When traffic load becomes very low, throughputs all approach to near value. This is because all MAC protocols have sufficient time to transmit packets from the source node to base station before the next packet generated. Nothing happens during the long time between two messages. In this case, it is worthless to spend more energy trying to increase throughput. Since there is not enough traffic, the throughput cannot be increased.

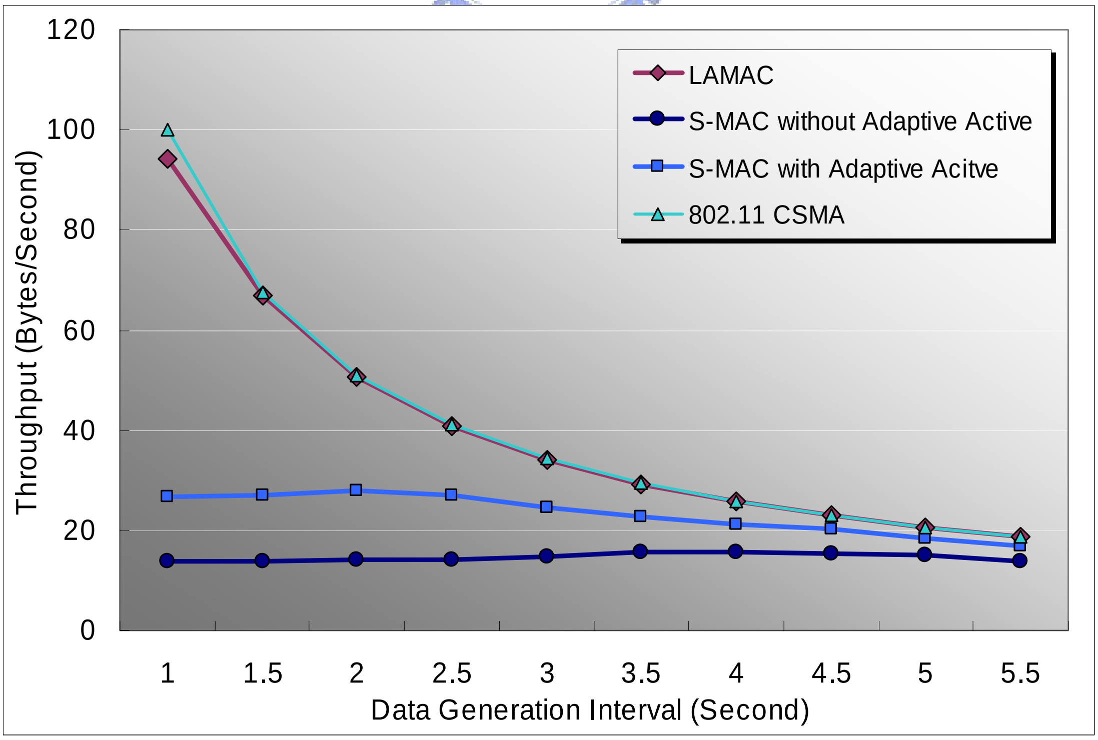

Figure 5-4： Throughput under different traffic load

Combining Figure 5-2, 5-3, and 5-4, we can know LAMAC not only reduces much transmission latency but also achieves quite good energy efficiency. In the following section, we will evaluation the performance of LAMAC on a more realistic network.

5.3 Evaluation on random distributed network

In the previous section, we evaluate the performance of different MAC protocols on a simple chain network. In the chain network, each node only contends the transmission medium with its previous and next hop nodes. And there is only one packet generation sensor node in the network. This kind of network is rare in real application. Thus we will evaluate the performance of each protocol on a more realistic network, a random distributed network, in this section.

The random distributed network is shown in Figure 5-5. This network contains 80 wireless sensor nodes and a base station. The base station is in the center and denoted by the computer-like symbol. Each black point in the figure denotes a sensor node. The lines between sensor nodes indicate they are within each other's communication range. For example, there is a line between node 1 and node 9. This means these two nodes can communication with each other without intermediate nodes. This network is a connected network. Each node has at least one path to base station. Every sensor node has its own unique ID which is expressed nearby. This ID is used for data gathering tree construction and data packets delivery.

Every sensor node in the network can generate data packets. The data packet generation could be event-driven or periodical generation. If the generation is event-driven, we will set a probability for sensor nodes to generate packets. For example, if this system is used as a fire detection system, we may set the probability to 0.0001%. This means every 10 days will a fire break out. However, if the probability is too small, our experiment will be difficult to proceed. Thus, in our experiment, we often set the probability to 1/2 or 1/10. If the generation is periodical, we set the packet generation interval to different value in order to reflect different traffic load. Every data packet will be forwarded to base station just like the previous experiment.

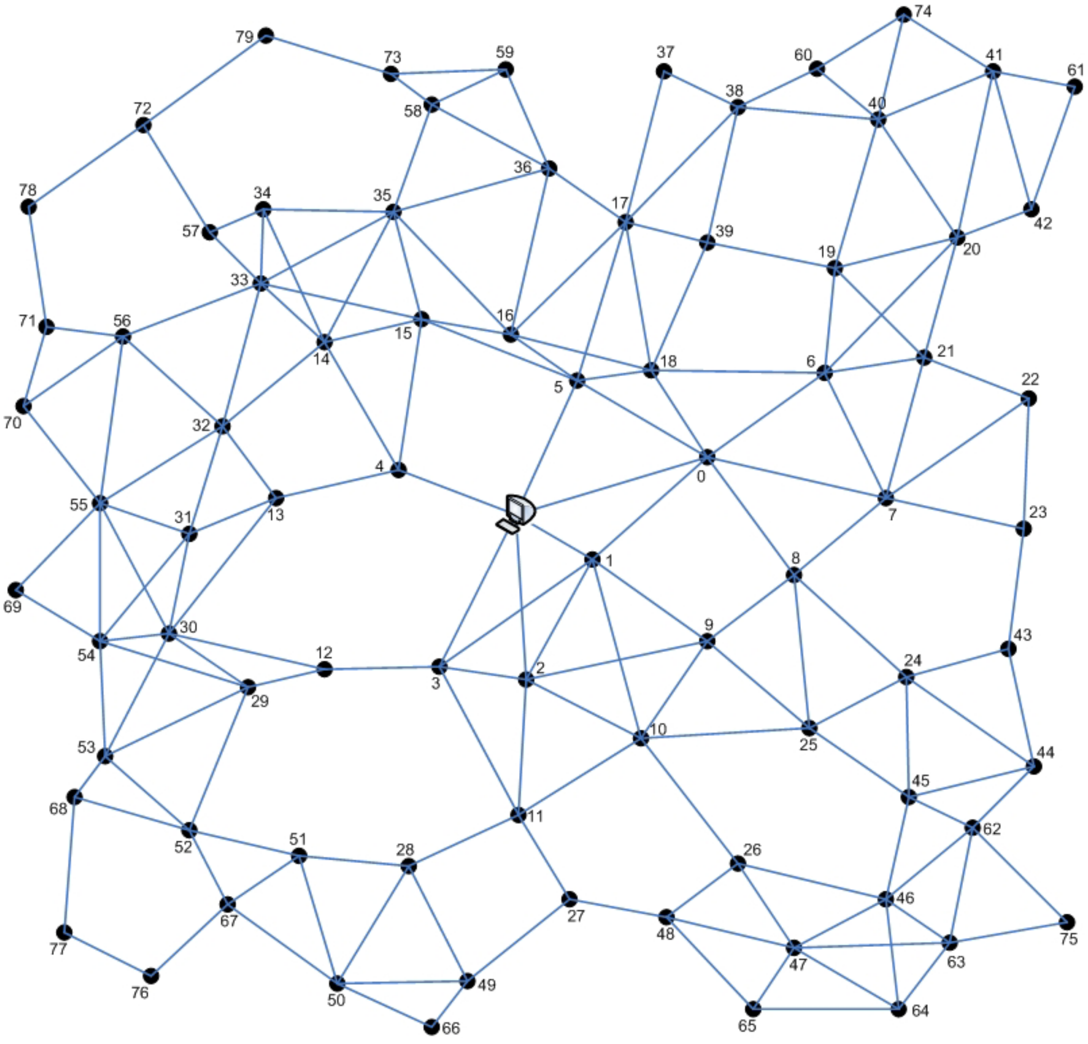

Figure 5-5： Random distributed network

5.3.1 Data gathering tree construction

Before evaluation, we need to construct the data gathering tree. As mentioned earlier, we use the similar scheme with ” NeuRFon Netform ” which is presented by L. Hester and Y. Huang. The data gathering tree is constructed according to the hop count of each node.

The data gathering tree is shown in Figure 5-6. The thick lines in the figure denote the backbone. And dotted lines indicate the two end nodes are in the same collision domain. If a node has 4 dotted lines, it will contend transmission medium with these 4 sensor nodes in the other end of these dotted lines. Every node views its next hop node toward base station as its parent node. If a sensor node gets packets to send, it forwards packets to its parent node. Every node only has one parent node but may have several children nodes.

Every node in the network determines its own wake-up schedule according to the depth in its routing path. The depth is calculated from the base station. Nodes which are one hop away from base station from level-1 nodes and have depth 1. Nodes which are within the communication range of level-1 nodes but are outside of the range of base station form level-2 nodes and have depth 2. The other levels are calculated in the same way. In Figure 5-6, we mark node’s depth together with its ID.

In order to show the backbone more clearly, we remove the dotted lines and only remain backbone in Figure 5-7. Figure 5-7 also shows the data packets transmission direction. According to our design of data gathering tree construction, the backbone will be renewed every certain interval in order to maintain the connectivity. Although the recommended interval of tree reconstruction is 95 seconds, the actual renewing interval depends on the stability of the network and can be changed by administrator.

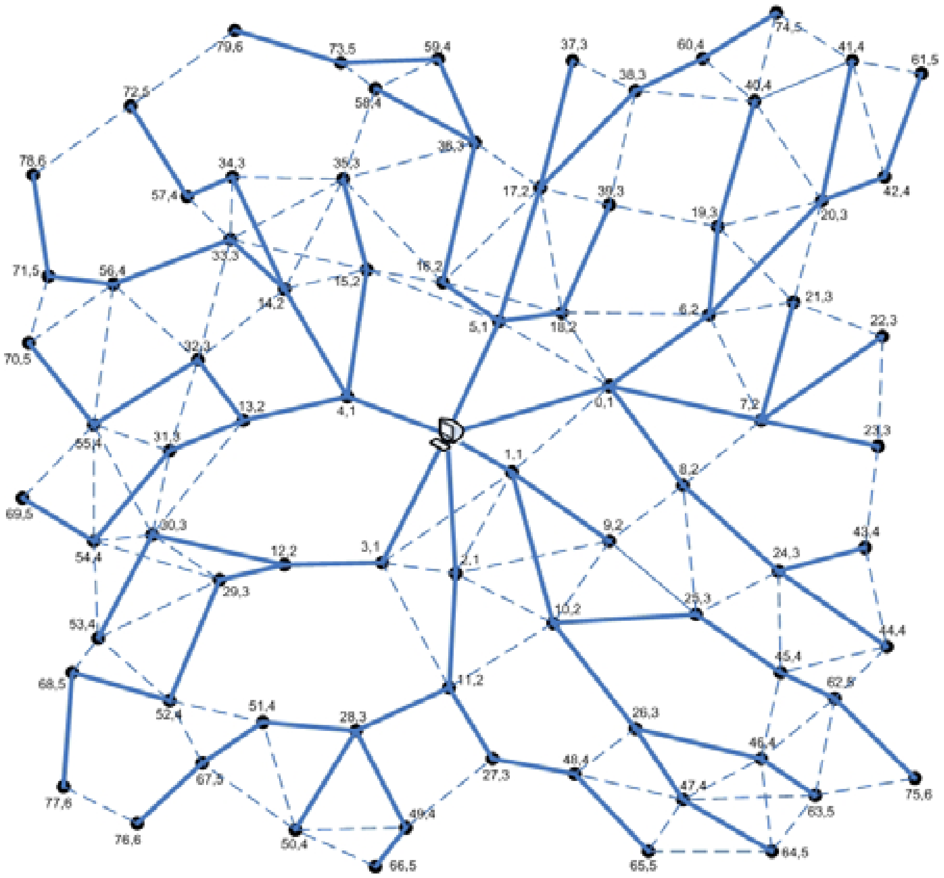

Figure 5-6： Data gathering tree with interference line

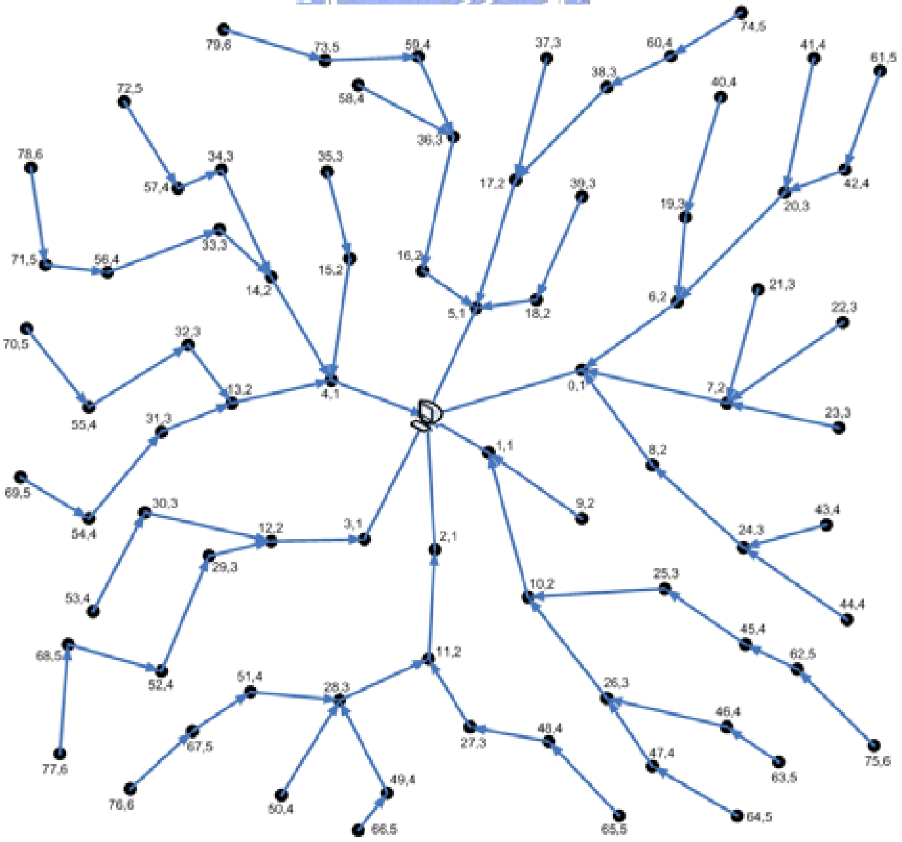

Figure 5-7： Data gathering with routing direction

In the following experiment, we implement three different MAC protocols to compare the performance. The three MAC protocols are LAMAC, S-MAC with adaptive active, and 802.11 CSMA. The reason we don’t implement S-MAC without adaptive active is because that its performance is much worse than it with adaptive active. Thus we just use S-MAC with adaptive active as a competition.

5.3.2 Evaluation with different Duty Cycle

In the first evaluation on the random distributed network, we take duty cycle as the control parameter to measure the performance of each MAC protocol. The value of duty cycle varies from 3% to 16%. When duty cycle is 3%, sensor nodes only work 0.09 second every 3 second in S-MAC and 0.12 second every 3.9 second in LAMAC. When duty cycle is 16%, sensor nodes work relatively more time. The parameter is used to adjust the percentage of active and sleeping period and also affects the lifetime of the whole network. The system is under medium traffic load to simulate an average case. The packet generation interval is one packet every 10 second at each sensor node.

Figure 5-8 shows the average transmission latency with different duty cycle. The result shows that LAMAC and 802.11 CSMA can achieve quite good transmission latency with different duty cycle. With 802.11 CSMA, the duty cycle can not affect its performance at all because it has no sleeping schedule and remain active all the time. With LAMAC, we can use active-sleep cycle more flexibly by using adaptive sleeping scheme. Whenever a sensor node gets packet to send, it can inform its parent node to reserve another extra adaptive active period to transmit this packet instead of waiting for the next frame. And when parent node receives the FRP packet, it also sends a FRP packet to its next hop node to reserve adaptive active period. The extra adaptive active period packet will propagate along the path and provides packets to be transmitted efficiently. Thus the duty cycle also doesn't affect LAMAC much. However, the result shows that S-MAC is affected by the duty cycle very seriously. Its performance gets worse with the increasing of duty cycle. The reason is that although S-MAC also use adaptive active scheme, it can not reserve the extra active period along the path. Packets only can be forwarded two hops away in a frame. If packets need to be forwarded more than two hops, they have to wait until the beginning of next frame. This means S-MAC can not use sleeping period efficiently.

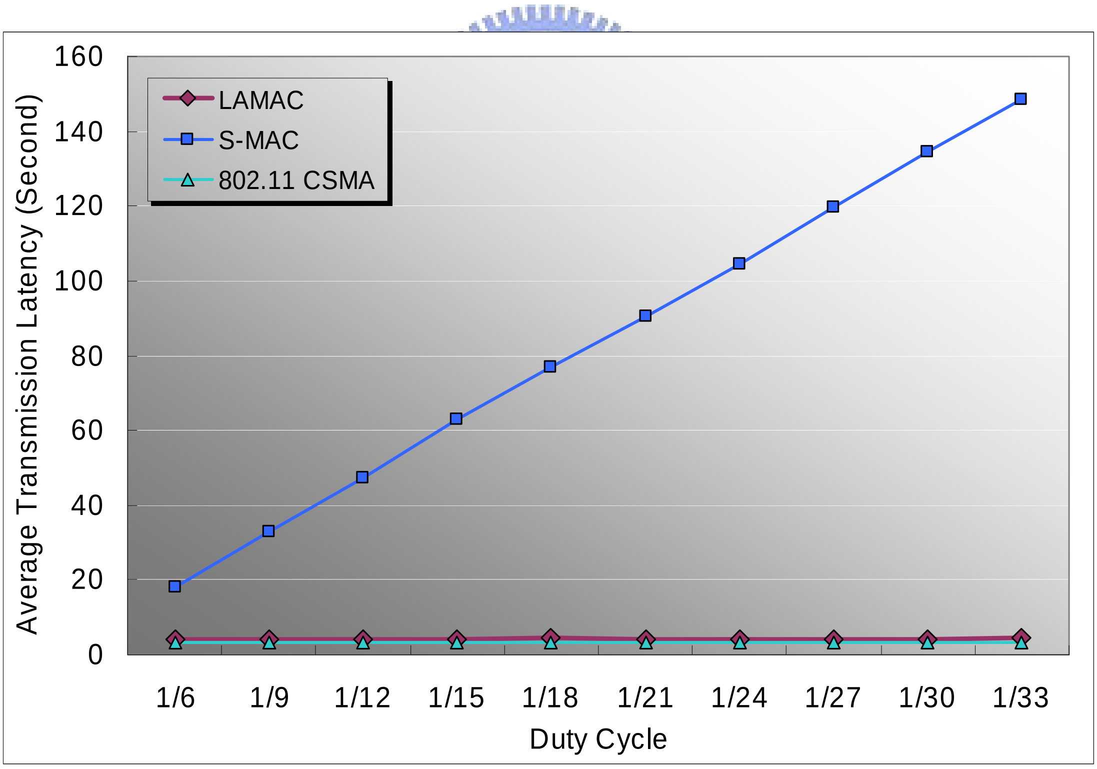

Figure 5-8： Average transmission latency with different duty cycle

Figure 5-9 shows the average energy consumption per packet with different duty cycle. The result shows that 802.11 CSMA uses much more power to transmit a packet than LAMAC and S-MAC. This extra energy consumption is caused by its full active schedule and idle listening problem. S-MAC uses about three times the energy than LAMAC. This is because S-MAC needs all nodes to wake up to transmit a little amount of packets. For example, there may be only one packet in the network. However, in order to put this packet one hop away, the whole sensor nodes need to wake up one time. Even with the adaptive active scheme, it still only can move this packet two hops away in a frame. Besides this, the adaptive active technique in S-MAC has an important drawback. It requires every node within the communication range of the sender and receiver to awake in the end of the current transmission. However, only one node will be the next active node. This means most nodes waste energy to perform the adaptive active procedure. Figure 5-9 shows LAMAC achieves the best energy efficiency. There is only a slight increasing of energy consumption when duty cycle is low. This is because our experiment is running under medium traffic load. And the low duty cycle is used for heavy traffic load. Thus, sensor nodes waste some energy in idle listening when there are no packets to send.

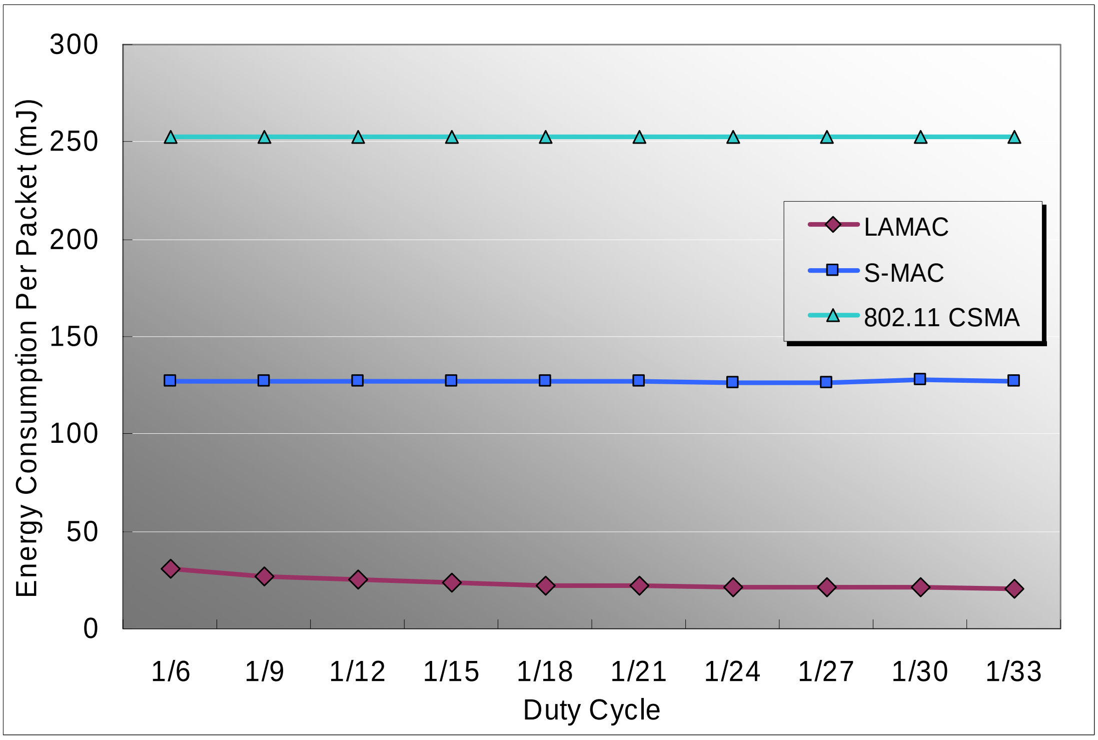

Figure 5-9： Energy consumption per packet with different duty cycle

Figure 5-10 shows the throughput with different duty cycle. The definition of throughput is the amount of data received by base station in a certain interval. In out experiment, the throughput means the amount of data which base station can receive every second. Figure 5-10 shows 802.11 CSMA has the best performance. This is because its full active schedule. LAMAC has the second throughput next to 802.11 CSMA and only has small difference with 802.11 CSMA. The result also shows the throughput of S-MAC is much worse than LAMAC. This is because every node has many interference nodes by using S-MAC. With LAMAC, sensor nodes only contend with nodes which are the same level. However, by using S-MAC, sensor nodes not only contend with the same level nodes but also the nodes which are the higher level and the lower level. Thus, its throughput is much worse than LAMAC.

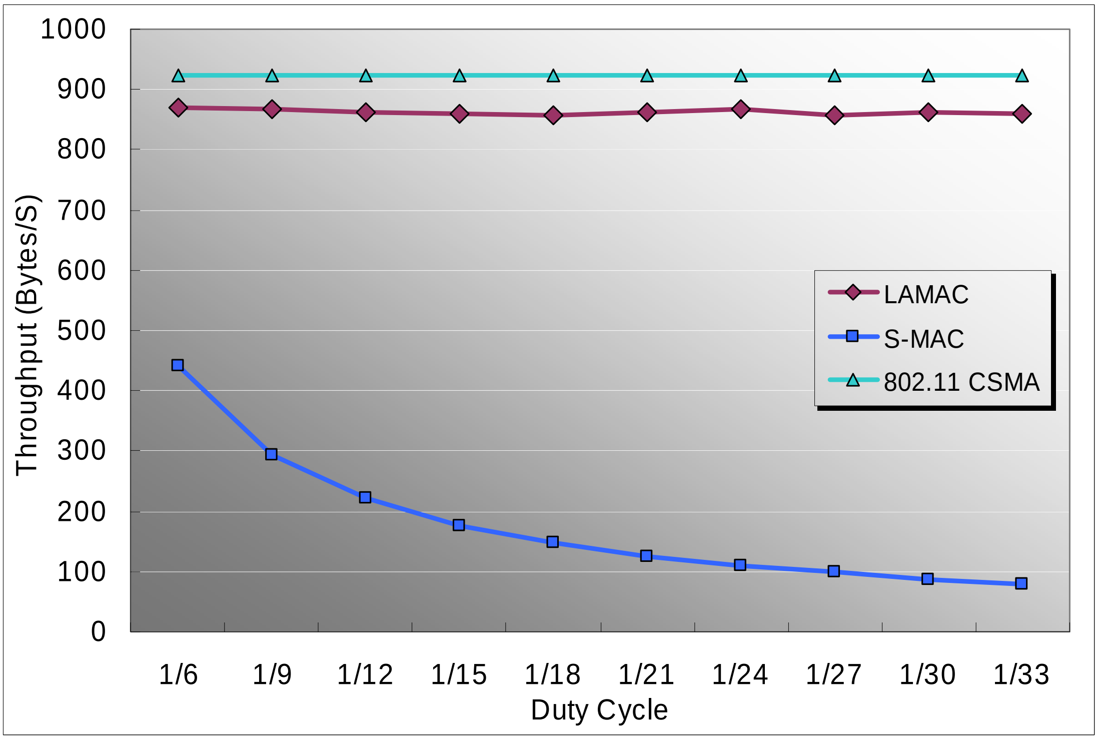

Figure 5-10： Throughput with different duty cycle

In the last evaluation with different duty cycle, we will measure the protocol work efficiency. Figure 5-11 shows the protocol work efficiency with different duty cycle. The result shows LAMAC uses energy much more effectively than others. Although S-MAC can extend the lifetime of the whole system by using periodical sleeping, it actually uses energy in the similar way with 802.11 CSMA when sensor nodes are in active period. In other words, S-MAC just extends the lifetime of system but not improve the usage of energy. Even though S-MAC uses the adaptive active technique, it can only improve the work efficiency slightly. On the contrary, LAMAC does improve the energy usage. We reduce the medium competition of each sensor nodes and increase the transmission probability. This makes the performance of LAMAC much better than others.

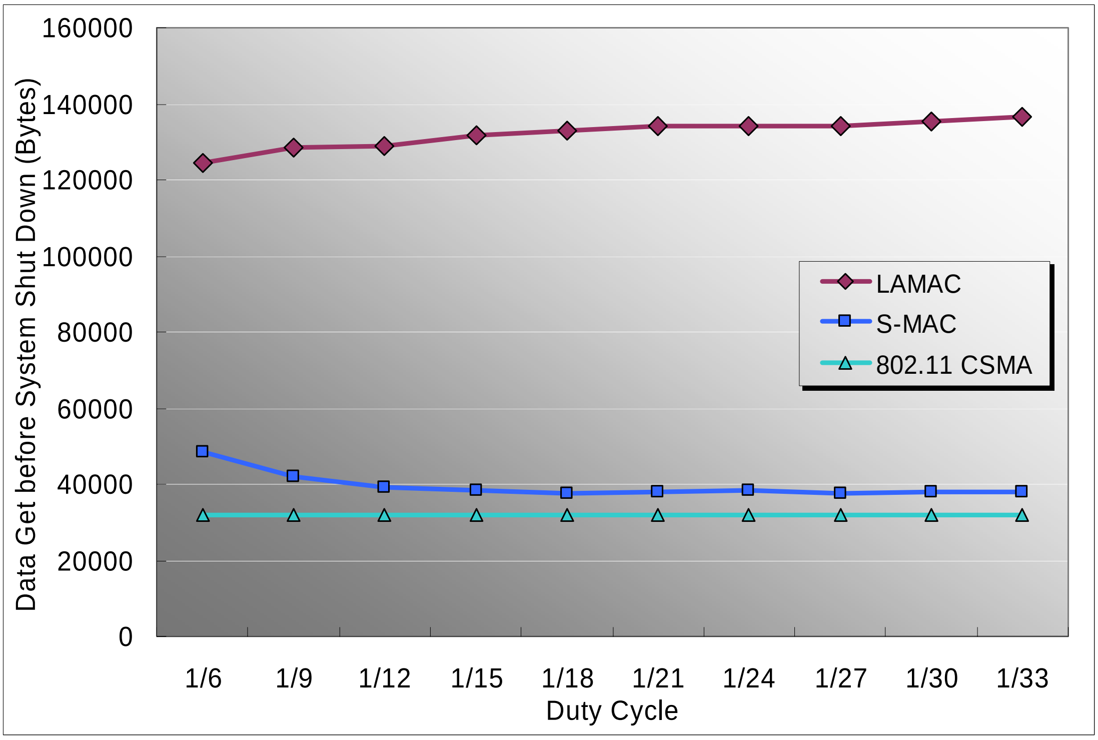

Figure 5-11： Data get with different duty before system shut down

5.3.3 Evaluation with different Traffic Load

In the following experiment, we will evaluate the performance of each MAC protocol under different traffic load. This experiment helps us to understand the adaptive ability to different traffic load of each protocol. As before, we change the traffic load by varying the interval period of packets. If the packet generation interval period is 5 s, a packet is generated every 5 second by each sensor node. In this experiment, the packet generation interval period varies from 1.2 second to 120 second. For the highest rate with a 1.2-s generation interval, the wireless channel is nearly fully utilized due to its low bandwidth. We have done 500 independent tests when using different MAC protocols with each different traffic pattern. In this experiment, we also use four metrics including average transmission latency, energy consumption per packet, throughput, and protocol work efficiency, to compare the performance of each MAC protocol.

Figure 5-12 shows the average transmission latency of each MAC protocol under different traffic load. The result shows that all MAC protocols all have higher latency under the higher traffic load. This is because before elder packets are transmitted to the base station, the new packets are generated due to the short generation interval. Thus, the elder packets need to contend the transmission medium with these newborn packets. This causes the transmission latency increases significantly. When the traffic load becomes medium, LAMAC and 802.11 CSMA both have ideal transmission latency reduction. This is because elder packets can be transmitted to the base station before next new packets generation time. In other words, the transmission latency of each packet is shorter than the packet generation interval. However, S-MAC can not achieve stable transmission latency even if the traffic load is medium. Until the generation interval is 72 second which means a low traffic load, S-MAC get the shortest latency. This is because S-MAC needs much more time to move the elder packets to base station. Only when the packet generation interval is long enough, e.g., 72 second, S-MAC can have enough time to transmit all the elder packets.

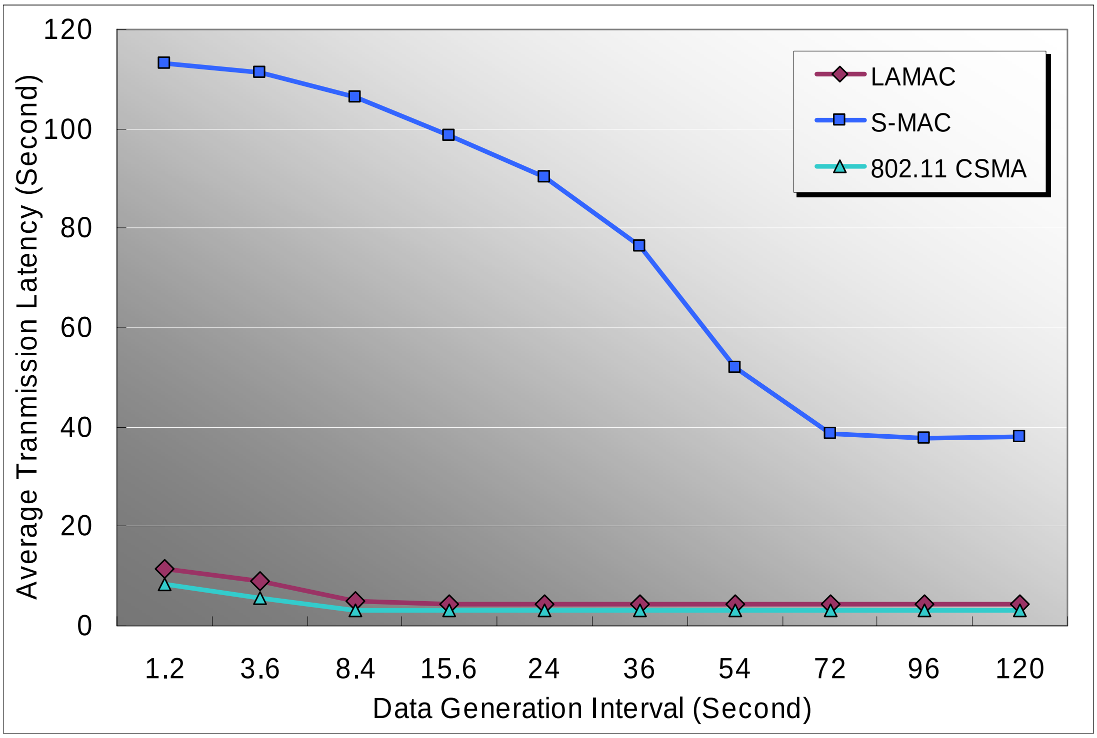

Figure 5-12： Average transmission latency under different traffic load

Figure 5-13 shows the energy consumption per packet under different traffic load. The energy consumption of each MAC protocol all increase with the increasing of the packet generation interval. This is because each protocol use more time in idle listening when traffic load is light. Before next new packets are generated, all sensor nodes still need to keep the wake-up schedule. And each active period all waste energy in idle listening because there are no packets to transmit. However, 802.11 CSMA uses the most energy compared with LAMAC and S-MAC. This is because its full active schedule. S-MAC also consumes more energy than LAMAC because it needs all sensor nodes to wake up for one time packet transmission. And the less probability of transmission also increases the energy consumption. Although LAMAC uses a little more energy to transmit a packet under low traffic load, the average energy consumption is still much better than the others.

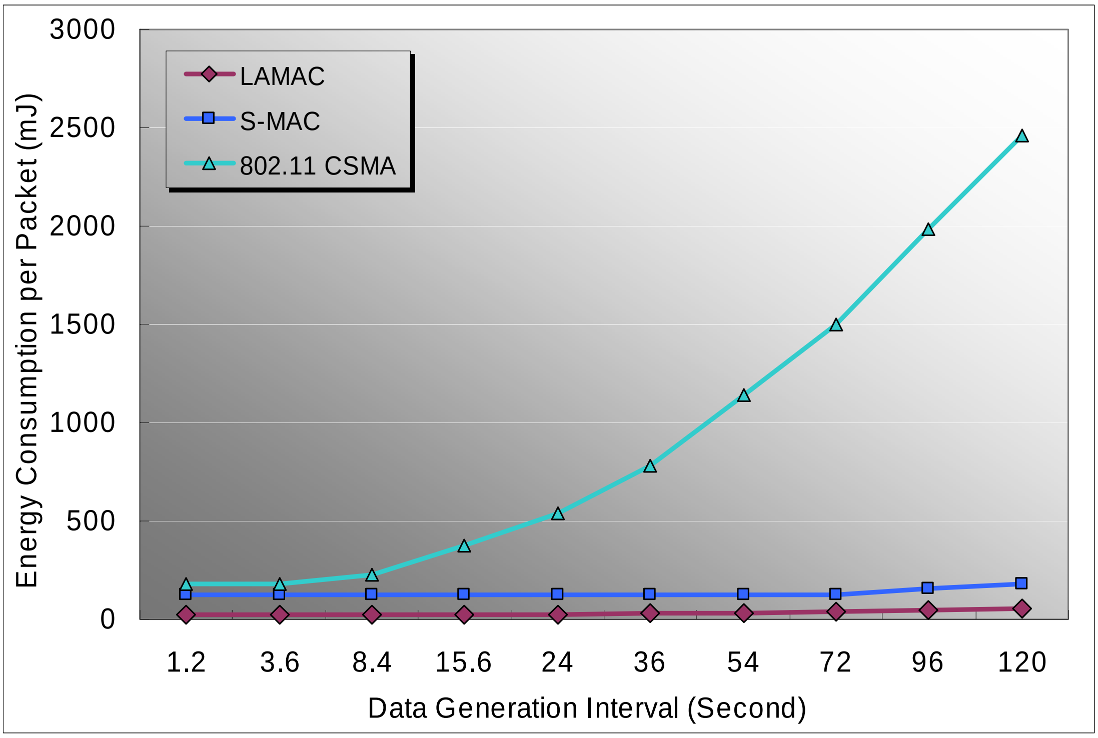

Figure 5-13： Energy consumption per packet under different traffic load

Figure 5-14 shows the throughput of each MAC protocol under different traffic load. The definition of throughput is the average amount of data received by Base Station every second. Thus, the value of throughput is affected by traffic load significantly. Reasonably, if the traffic load becomes light, the throughput will decrease with the same ratio. On the contrary, if the traffic load becomes high, the throughput will increase with the same ratio. However, not only traffic load will affect the throughput. The transmission latency also affects the throughput. If a MAC protocol has higher latency than others, its throughput must also lower than others. If with the same protocol, there are still some differences of transmission latency under different traffic load. Thus, the throughput may not have the same ratio of change with the increasing or decreasing of the traffic load. The result shows that the throughput of LAMAC and 802.11 CSMA both decrease slowly under the high traffic load. However, after the packet generation interval becomes longer than 8.4 second. The throughput of LAMAC and 802.11 CSMA both have the same ratio of change with the variation of traffic load. The result also shows that S-MAC much less throughput than LAMAC under the light traffic load. This is because S-MAC has high transmission latency when traffic load is high and medium. This high transmission latency significantly reduces the throughput of S-MAC.

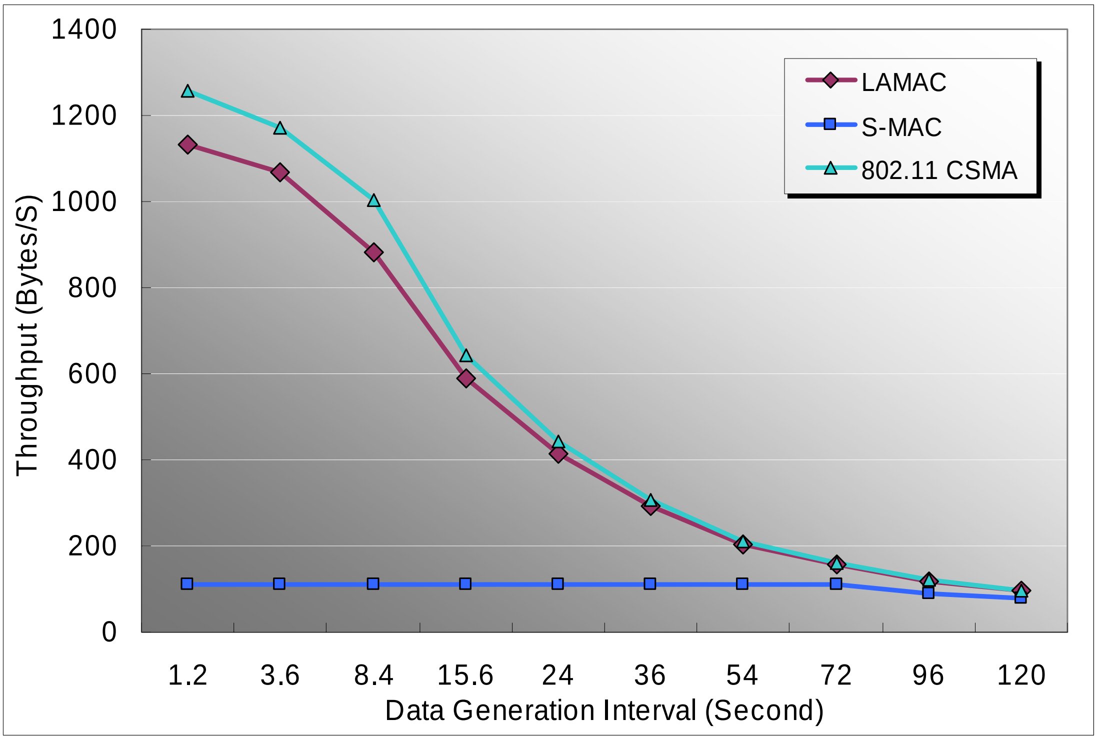

Figure 5-14： Throughput under different traffic load

Figure 5-15 shows the protocol work efficiency under different traffic load. The result shows LAMAC has the best performance. There are two turning points in the curve of LAMAC. The first point is in the value of 3.6 and the second is in 15.6. When packet generation interval is shorter than 3.6, the traffic is heavy. Elder packets need to contend with the newborn packets. The extra contention wastes lots of energy. Thus, although traffic load is high, the amount of packet received can not increase before level-1 nodes exhaust their energy. The higher the traffic, the more energy wastes in the contention. When packet generation interval is higher than 3.6, the contention times decrease. The work efficiency increases with the decreasing of traffic load. However, when the generation interval is longer than 15.6, the work efficiency decreases again. Most sensor nodes waste energy on idle listening because there are no packets to transmit. The situation is getting worse when the generation interval becomes longer. Thus, we have the second turning point at 15.6. S-MAC has the second performance next to LAMAC. The reason which makes S-MAC have almost the same value of work efficiency between 1.2 and 36 is similar to the reason of LAMAC between 1.2 and 3.6. The result shows S-MAC has high transmission latency when packet generation interval is shorter than 36. This means there are a lot of contentions among sensor nodes in this situation. When generation interval is longer than 36 and shorter than 54, the contention times decrease and the work efficiency increases. However, when the generation interval is longer than 54, S-MAC suffers the idle listening problem. The performance decreases with the increasing of packet generation interval. 802.11 CSMA has the worst performance. Because of its low transmission latency, 802.11 CSMA suffers idle listening problem when packet generation interval is longer than 3.6. When the interval is longer than 3.6, the performance of 802.11 CSMA decreases with the traffic load.

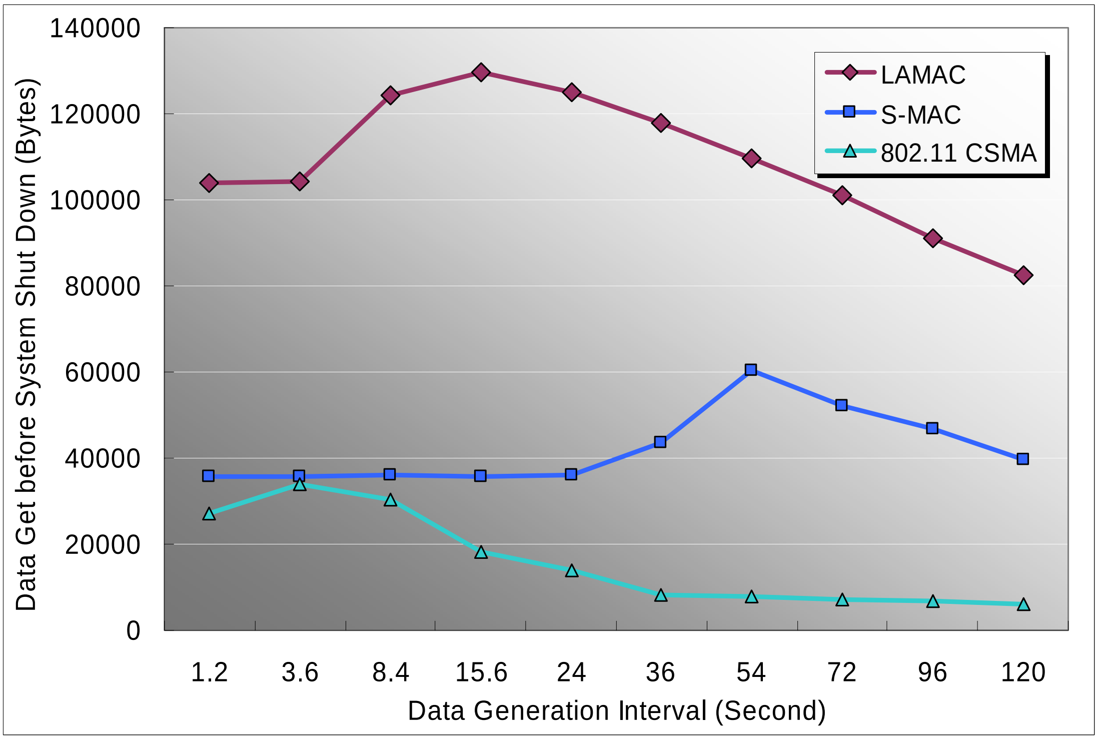

Figure 5-15： Data get under different traffic load before system shut down

5.3.4 Evaluation with different Transmission reliability

The most important feature of wireless sensor networks is its unreliability of transmission. Each node may suffer different sources which make it unable to receive data. These sources may be interference of other sensor nodes or the environment. In the following experiment, we will evaluate the performance of each MAC protocol with different transmission reliability. We will use two metrics, transmission latency and energy consumption, to compare the performance of each protocol.

In the following experiment, we let each transmission has different failure probability. In the most reliable condition, each transmission has 0% probability of transmission failure. And we let this probability increase from 0% to 90%. In the most unreliable condition, each transmission only has 10% probability to transmit a packet successfully. By varying the transmission failure probability, we can know the adaptive ability to unreliable networks of each MAC protocol.

Figure 5-16 shows the average transmission latency of each MAC protocol with different transmission failure probability. In all three MAC protocols, the latency increases exponentially with the transmission failure probability. However, S-MAC has much higher transmission latency than the other two. This is because each packet has to wait for one sleep cycle when the transmission fails. The latency of LAMAC, by comparison, is very close to that of 802.11 CSMA. This is because the adaptive sleeping scheme often allows LAMAC to retransmit a packet quickly. When traffic load is heavy or medium, sensor nodes are always in adaptive sleeping mode. Thus, packets only have to wait until next adaptive active period. The length between two adaptive active periods is quite shorter than the length of a sleeping cycle. Due to the reason, the transmission failure probability affects us much less than S-MAC.

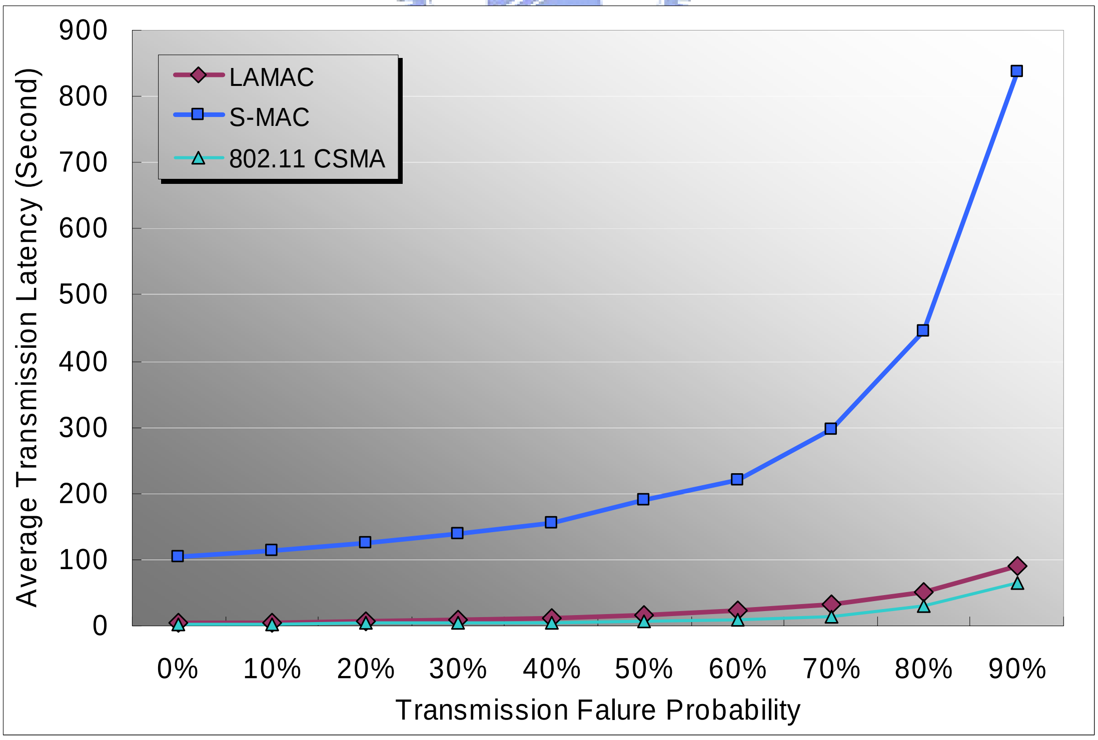

Figure 5-16： Average transmission latency with different transmission failure probability

Figure 5-17 shows the energy consumption per packet with different transmission failure probability. The result shows the energy consumption of all protocols increases with the transmission failure probability. This is because sensor nodes waste energy to contend and transmit when transmission failure happen. With the increasing of failure probability, this kind of energy waste also increases. Actually, all three MAC protocols have the same increasing ratio with the transmission failure probability. However, LAMAC still achieves the best energy efficiency with different failure probability.

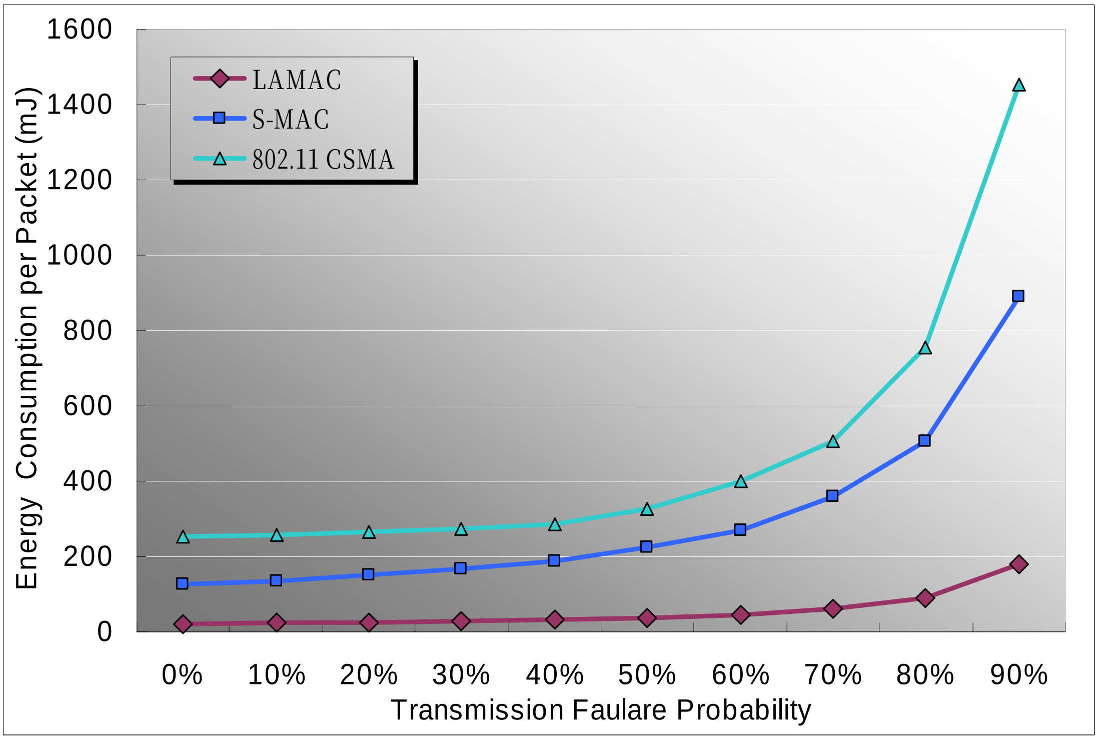

Figure 5-17： Energy consumption per packet with different transmission failure probability

5.3.5 Evaluation of the integration performance

In the last experiment, we look at the integration performance that LAMAC has made on energy consumption, transmission latency from the above measurement. This evaluation is used to understand if LAMAC succeeds in reducing overall resource cost to transmit packets.

To evaluate the combined effect of energy consumption and transmission latency, we calculate the per-byte cost of time and energy to transmit data from the source nodes to the base station under different traffic load. The transmission failure probability of 20% is used in this experiment in order to simulate the realistic network.

The result is shown in Figure 5-18. The figure shows that when traffic load is very heavy, LAMAC and 802.11 CSMA both show statistically much better performance than S-MAC. Under this heavy traffic load, LAMAC and 802.11 CSMA are always active, while the added latency of S-MAC requires extra transmission time and lowers the performance.

At lower traffic load, 802.11 CSMA quickly exceeds the cost of S-MAC. This is because the energy consumption of 802.11 CSMA grows significantly under light traffic load as shown in Figure 5-13. S-MAC has better performance when traffic load is light. The result indicates the benefits of periodical sleeping and adaptive active occur under light traffic load. However, the best performance is still LAMAC.

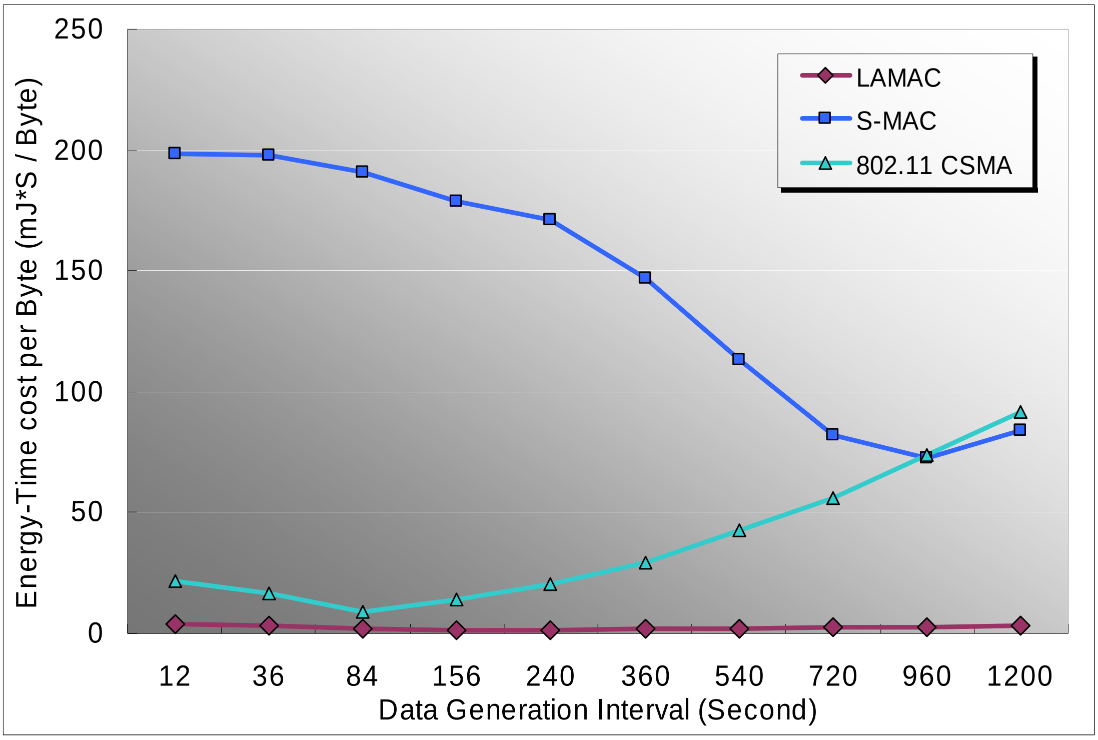

Figure 5-18： Integration performance under different traffic load

6. Conclusion

This paper presented a new Medium Access Control protocol, the LAMAC protocol, for wireless sensor networks. It exploits the application specific characteristics of sensor networks to meet their limited energy, short transmission latency, and throughput requirements.

Energy efficiency is the most important issue of designing MAC protocol for wireless sensor networks. The existing paper all addressed on this topic and got good achievement. But the trade-off of increasing transmission latency has become a very serious problem. The proposed LAMAC protocol introduced a new scheme which not only conserves energy but also reduces transmission latency greatly.

The basic scheme of LAMAC is to arrange the active-sleep cycle schedule of each sensor node according to its location in the data gathering tree. When a data packet transmitted through the network, the continuous wake-up nodes will forward it to base station quickly.

Besides the basic scheme, we introduced a technique called adaptive sleeping scheme for LAMAC to adapt different traffic load and solve the interruption problem of contention mechanism. This adaptive sleeping scheme is proposed to request sensor nodes remain awaken when there are more packets destined to them. By using this scheme, the active-sleep cycle can be used more flexibly and efficiently.

Based on experiments, we observed that LAMAC has much less transmission latency and conserves more energy compared to S-MAC and full active 802.11 CSMA. Our experiment also simulated the unreliability of wireless sensor networks. The result has shown that LAMAC still achieves very good performance in unreliable sensor networks.

7. References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A Survey on Sensor Networks,” IEEE Communications Magazine, pages 102-114, August, 2002.

[2] R. Cristescu, B. Beferull-Lozano, and M. Vetterli, “On network correlated data gathering,” Conference of the IEEE Communications Society (IEEE Infocom), 2004.

[3] S. Slijepcevic, M. Potkonjak,V. Tsiatsis, S. Zimbeck, M. B. Srivastava, ”On communication Security in Wireless Ad-Hoc Sensor Network,” Eleventh IEEE International Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises, June 10 - 12, 2002.

[4] S. Pattem, B. Krishnamachari, and R. Govindan, “The impact of spatial correlation on routing with compression in wireless sensor networks,” in ACM/IEEE International Symposium on Information Processing in Sensor Networks, 2004.

[5] C. Intanagonwiwat, R. Govindan, and D. Estrin. “Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks,” In Proceedings of the Sixth Annual International Conference on Mobile Computing and Networks, Boston, Massachusetts, August 2000.

[6] L. Hester, Y. Huang, O. Andric, A. Allen, and P. Chen, “The neuRFon Network: A Self-Organizing Wireless Sensor Network,” to appear in the IEEE 11th International Conference on Computer Communication and Networks, October 2002.

[7] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson, “Wireless

Sensor Networks for Habitat Monitoring," ACM International Workshop on Wireless Sensor Networks and Applications, Atlanta, Georgia, USA, September 2002.

[8] T. van Dam and K. Langendoen, "An adaptive energy-efficient mac protocol for wireless sensor networks," In Proceedings of the First ACM Conference on Embedded Networked Sensor Systems, 2003.

[9] C. Lin, C. Federspiel, and D. Auslander, "Multi-Sensor Single Actuator Control of HVAC Systems," International Conference for Enhanced Building Operations, 2002.

[10] N. Xu, "A survey of sensor network applications," 2004, available at http://enl.usc.edu/ningxu/papers

[11] K. Schwieger and G. Fettweis, "Multi-hop transmission: Benefits and deficits," In Proc. GI/ITG Fachgespraech Sensornetze. Karlsruhe, Germany, 26.-27. February 2004.

[12] M. Stemm and R. H Katz, "Measuring and reducing energy consumption of network interfaces in hand-held devices," IEICE Transactions on Communications, vol. E80-B, no. 8, pp. 1125–1131, Auguest. 1997.

[13] O. Kasten, "Energy Consumption," http://www.inf.ethz.ch/˜kasten/research/bathtub/energy_consumption.html, Eldgenossische Technische Hochschule Zurich, November 2001.

[14] H. Wang, J. Elson, L. Girod, D. Estrin, and K. Yao. "Target classi-cation and localization in habitat monitoring," In Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing 2003, Hong Kong, April 2003.

[15] T. S. Rappaport, "Wireless Communications, Principles and Practice," IEEE Press Prentice Hall, 1996.

[16] J. C. Haartsen, “The Bluetooth radio system,” IEEE Personal Communications Magazine, pp. 28-36, February 2000.

[17] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-efficient communication protocols for wireless microsensor networks,” Hawai International Conference on System Sciences, January 2000.

[18] A. D. Amis, “Max-min D-Cluster Formation in Wireless Ad Hoc networks,” Conference of the IEEE Communications Society, March 2000.

[19] M. Gerla and J. T. Tsai, “Multicluster, Mobile, Multimedia Radio Network, Wireless Networks,” ACM Baltzer Journal of Wireless Networks 1995.

[20] K. Sohrabi, “Protocols for Self-Organization of aWireless Sensor Network,” IEEE Personal Communications, October 2000.

[21] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-efficient communication protocols for wireless microsensor networks,” in Proceedings of the Hawaii International Conference on Systems Sciences, Janarery. 2000.

[22] S. Intille, “Designing a home of the future,” IEEE Pervasive Computing, April 2002.

[23] L. Schwiebert, S. Gupta, and J.Weinmann, “Research challenges in wireless networks of biomedical sensors,” In Proceedings of the Seventh Annual International Conference on Mobile Computing and Networking, 2001.

[24] D. Malan, T. Fulford-Jones, M. Welsh, and S. Moulton, “Codeblue: An ad hoc sensor network infrastructure for emergency medical care,” In Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks, 2004.

[25] B. Krishnamachari, D. Estrin, and S. Wicker, “The impact of data aggregation in wireless sensor networks,” in International Workshop on Distributed Event-Based Systems, 2002.

[26] D. Estrin, R. Govindan, J. Heidemann and S. Kumar, "Next Century Challenges: Scalable Coordination in Sensor Networks," In Proceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking, August 1999

[27] S. Tilak, N. Abu-Ghazaleh, and W. Heinzelman, "A Taxonomy of Wireless Microsensor Network Models," ACM Mobile Computing and Communications Review, 2002.

[28] ASH Transceiver TR3000 Data Sheet [Online]. Available: http://www.rfm.com/

[29] IEEE Std 802.11e, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications," IEEE LAN MAN Standards Committee of the IEEE Computer Society. IEEE Std 802.11, 1999.

[30] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: a media access protocol for wireless LAN's," In Conference on Communications Architectures, Protocols and Applications, pages 212–225, London, August 1994.

[31] M. Stemm and R. H. Katz, "Measuring and reducing energy consumption of network interfaces in hand-held devices," IEICE Transaction Communication, Auguest, 1997.

[32] S. Singh and C. S. Raghavendra, "PAMAS: Power aware multi-access protocol with signalling for ad hoc networks," ACM Computer Communications, July 1998.

[33] C. Guo, L. C. Zhong, and J. M. Rabaey, "Low-Power Distributed MAC for Ad Hoc Sensor Radio Networks," Proceeding Internet Performance Symposium, November 2001

[34] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient mac protocol for wireless sensor networks," Conference of the IEEE Communications Society

(IEEE Infocom), June 2002.

[35] C. Schurgers, V. Tsiatsis, S. Ganeriwal, and M. Srivastava, “Optimizing Sensor Networks in the Energy-Latency-Density Design Space,” IEEE Transactions on Mobile Computing, vol.1, no.1, January-March 2002.

[36] Y. Yu, B. Krishnamachri, and V. K. Prasanna, “Energy-Latency Tradeoffs for Data Gathering in Wireless Sensor Network”, Conference of the IEEE Communications Society (IEEE Infocom), 2004.