An Efficient MAC Protocol Based on Hybrid Superframe for Wireless Sensor Networks

Ge MA

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ABSTRACT

An Efficient MAC Protocol Based on Hybrid Superframe for Wireless Sensor Networks

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The usage of wireless channels is based on Media Access Control (MAC) protocols, which allocate wireless resources and control the way that sensors access a shared radio channel to communicate with their neighbors. Designing low energy consumption, high efficiency MAC protocols is one of the most important directions in Wireless Sensor Networks (WSN). So far, MAC protocols in WSN are usually divided into two categories: contention-based MAC protocols and schedule-based MAC protocols. However, both protocols have their own advantages and disadvantages that sometimes it is hard to decide which one is better than the other one. A hybrid protocol is concerned a lot now in WSN, which is IEEE 802.15.4. It integrates the advantages of both contention-based and schedule-based mechanisms. However, this protocol has some improving spaces as well, which motivated us to further study it and proposed a new contention reserve MAC protocol, named CRMAC, under the inspiration of IEEE 802.15.4's superframe structure. Through a series of theoretical and simulation analysis, we show that CRMAC performs better in energy consumption, system delay and network throughput than IEEE 802.15.4 and LEACH (Low Energy Adaptive Clustering Hierarchy). CRMAC is especially suitable for short packet transmission under low traffic networks, which is the main situation in WSN, so this protocol is practical in WSN.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
ACK	Acknowledgment
CAP	Contention Access Period
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CFP	Contention Free Period
CSMA/CA	Carrier Sensor Multiple Access/Collision Avoidance
CTS	Clear-to-Send
DCF	Distribution Coordination Function Inter-frame Space
DIFS	Distributed Coordination Function
FDMA	Frequency Division Multiple Access
FFD	Full-Function Device
GTS	Guaranteed Time Slots
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IT	Information Technology
LEACH	Low Energy Adaptive Clustering Hierarchy

LR-WPAN	Low Rate Wireless Personal Area Network
MAC	Medium Access Control
MEMS	Micro-Electro-Mechanical System
MIT	Massachusetts Institute of Technology
OSI	Open System Interconnection
QoS	Quality of Service
REQ	Request
RFD	Reduced-Function Device
RTS	Request-to-Send
SIFS	Short IFS
S-MAC	Sensor Medium Access Control
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
WLAN	Wireless LAN
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
μAMPS	μ Adaptive Multi-domain Power aware Sensors

CHAPTER 1

INTRODUCTION

1.1 Introduction

According to the rapid development and growing maturity of technology such as mobile communication, embedded computing technology, MEMS (Micro-Electro-Mechanical Systems) and wireless sensors, it becomes possible now that a large amount of low-cost wireless sensors can create a wireless sensor network (WSN) by mobile links. If we say Internet creates a logical information world, which changes the way of communication between people, WSN then merges this logical information world with objectively existed physical world, which will change the way of communication between people and nature. Among various forecast reports for future technology development, U.S. Business Week identified WSNs as one of the 21 most important technologies for the 21st century [1]; while MIT Technology Review ranked it among the top 10 emerging technologies that will change the world [2]. No doubt the development of WSNs will be an enormous driving force to the development of modern technology.

A WSN is made of large amount of microsensor nodes, which contain wireless communication and computing ability. These nodes are spread out in or near the target objects within an application area and form a multi-hop, self-organized network system by wireless communication. The purposes of them is to coordinately sense, collect and process the information in the cover area and forward them to the observers by various methods – mainly refer to different media access control (MAC) protocols. Nodes in a sensor network are usually close to each other and they communicate with each other by multi-hop wireless communications. Thus, sensors, objects being sensed (i.e. "the objects") and the observer constitute three essentials in a WSN.

Comparing to traditional wired sensor networks, WSN has some unique characters such as flexible placement, simple expansion, and so on. The place and topology of wireless sensors can be designed either in advance, or be spread randomly. These nodes then form the network and complete certain tasks. WSNs can be widely used in many situations, such as forest fire detection, intelligent agriculture, environment and pollution monitoring, traffic control, industrial control, home automation, etc. It also has practical applications in military and security fields, such as battlefield reconnaissance/surveillance, military targets protection, and more. Figure 1-1 shows the structure of a WSN with sensors spread in it.

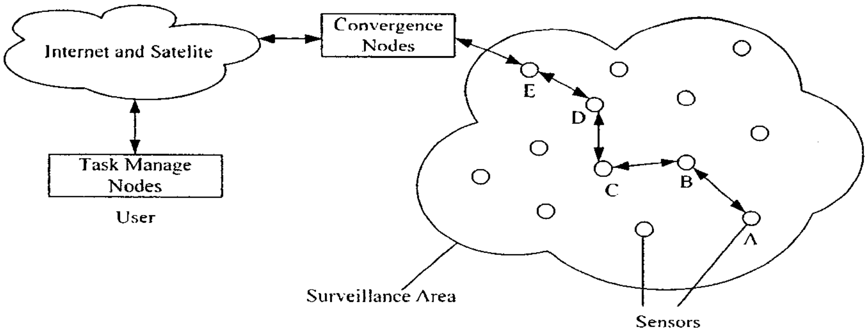


Figure 1-1 Structure of a Wireless Sensor Network

Traditional wireless self-organized networks are made of dozens to hundreds of nodes. It is a kind of mobile peer-to-peer networks which using wireless communication and dynamic organization to transmit high quality of service (QoS) of multimedia information flow through the use of dynamic routing and mobile management technology. Usually nodes have continuous energy supplied.

Although similar points can be highlighted between wireless self-organized networks and wireless sensor networks, they have visible differences as well. The most obvious ones are listed below:

1. WSN is a network that integrates monitoring, controlling, and wireless communicating. The number of nodes is much larger (thousands to even dozens of thousands) and nodes are spread more intensively.
2. Sensor nodes are usually battery-powered, thus due to its environmental impact and energy depletion, nodes are more prone to fault.
3. In addition, sensor nodes have limited processing ability, storage capacity and communication capability.

4. Environmental interference and node failures could easily lead to the changes in the structure of network topology.

In WSNs, media access Control (MAC) protocols decide the way of using wireless channels. They allocate the finite wireless resources among wireless sensors and build the underlying basic infrastructure of WSN systems.

MAC protocols are in the lower layer of the protocol, which have big influence on the performance of WSNs, it is the key network protocols to assure normal WSN communications. Thus, designing appropriate MAC protocols has significant importance for WSN.

1.2 Problem Statement and Motivation

The research points of wireless communication network now more and more focus on how to strengthen the capability of WLAN and developing new communication methods to adapt to the increasing application demand. Therefore, the concept of Low-Rate Wireless Personal Area Network (LR-WPAN) comes out. Along with the fast development of WSN technology, this standard also gained great growth since it also fits well in WSNs. Among them, IEEE 802.15.4 standard defines interconnections and agreements between devices through radio frequency in personal local area networks (LANs). This standard supports both star networks and peer-to-peer networks which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as media access mechanism and also provides superframe structure as a complimentary program.

Since delay and throughput are two important parameters to evaluate the performance of MAC protocols. Meanwhile, restricted energy should be the first priority of consideration when designing the protocols for WSN. Superframe structure acts as an efficient channel allocation method, which contains both contention phases and schedule phases. This hybrid MAC protocol ensures the flexibility of access and meanwhile balances some requirements in QoS bandwidth and flow. However, Guaranteed Time Slot (GTS) in the superframe structure of IEEE 802.15.4 must be reserved in the previous superframe; this character makes delay in GTS not as ideal under higher requirement to time efficiency. Besides, the requirements of GTS can only be applied by the devices that are already built up connection, and its basic method to build up the connection is still contention-based mechanism–Slotted CSMA/CA. Thus, this protocol cannot jump out from the restriction of contention-based mechanism in terms of energy consumption, throughput, etc.

Comprehensively analyze the problems existed in IEEE 802.15.4 above, and borrow the idea of combining contention-based and schedule-based MAC protocols together, we proposed a new intra-cluster MAC protocol aimed at higher time efficiency requirements GTS applications in WSN, we expect it can further shorten the communication delay and obtain higher energy efficiency and network throughput as well. We hope this can provide a new channel access plan for WSN in commercial and industry surveillance that has the requirements such as big quantity of data, long life-circle, etc.

1.3 Summary of Main Contributions

This thesis will be based on a deep analysis of IEEE802.15.4's superframe structure, by comprehensively considering the pros and cons of contention-based and schedule-based mechanisms, we proposed an improved MAC protocol - Contention Reserve MAC protocol - CRMAC, which is suitable for WSN.

Main contributions of this thesis are as follows:

1. Proposal of a novel MAC protocol – Content Reserve MAC (CRMAC) Protocol, whose characters are listed as follows:

- CRMAC uses an active-trigger communication mechanism, sensor nodes send communication request only when it detected abnormal events;
- CRMAC protocol combines contention-based mechanism and schedule-based mechanism, which involved both of their advantages to achieve better network performance;
- Contention-based MAC protocols are flexible to configure which makes this kind of protocols have very good scalability. Communication reserving information in CRMAC uses time-limited, centralized contention access, which is more flexible in reservation, in this phase, if the reserving short packets has collisions and retransmissions, it will consume lower energy compared to IEEE 802.15.4, thus this protocol has better energy efficiency;
- Compared to IEEE 802.15.4's "data transmission mechanism mainly depends on contention access and is supplemented by GTS" structure, CRMAC adopts TDMA schedule mechanism for data communication in CRMAC. During the transmission of important data packets, this will efficiently prevent the collisions and retransmissions, hence decreases the channel resource wastes due to them and increases the network throughput and delay.

2. Further analysis and establish mathematical model of energy consumption in CRMAC, which is the most important network performance indicator in WSNs.
3. Through simulations, we compare CRMAC with IEEE 802.15.4 as well as with LEACH in energy consumption, system delay, network throughput and life-cycle.

1.4 Organization

The remainder of the thesis is structured as follows:

Chapter 2 presents background information and related work to MAC protocols in WSNs. It introduces major criterions for MAC protocols and the cause of energy waste. For the related work, we will compare contention-based MAC protocols with schedule-based MAC protocols. For the first kind of protocols, we will describe the protocols such as WiseMAC, S-MAC, and T-MAC. For the other kind of MAC protocols, we will introduce TDMA-based schemes, LMAC and BMA. Then we will describe IEEE 802.15.4 standard, which integrates both schedule-based and contention-based protocols. Furthermore, we will discuss the conventional cluster-based protocol -- Low-Energy Adaptive Clustering Hierarchy (LEACH).

In Chapter 3, we will present the proposed Contention-Reserve MAC (CRMAC) protocol in detail. We will also setup the markov chain model for CRMAC protocol and analyze the energy consumption based on it.

In Chapter 4, we will present simulation results and analysis. A description of the simulation model is followed through the experimental results.

Finally, the paper concludes with Chapter 5, which also discusses future works.

CHAPTER 2

BACKGROUND AND RELATED WORK

In a WSN, a number of nodes share transmission medium, in order to ensure the network works normally and data transmits smoothly, some mechanism must be added to determine which device will occupy the medium and transmit data in the following time slot. Therefore data link layer need to have media access control (MAC) function. Main functions of MAC protocol include: data frame assembling/uninstalling; frame addressing and identification; frame receiving and transmitting as well as link management, error control, etc. The most important function of MAC layer is to decide channel access allocation, which logically shields the differences among different types of physical links.

WSNs are different from other wireless networks, which the vast majority of its devices and sensors use micro-battery (usually an AA or button battery) to act as power supply, thus the energy of devices and sensors in the networks are extremely restricted. When designing WSNs, no matter which protocol to choose, energy consumption will be the first priority of consideration even at the expense of other properties (such as delay, throughput and fairness, etc).

MAC protocols directly control RF modules, which have important impact on nodes' energy consumption. Therefore, MAC layer, which stays in the lower part of protocol stack, has great impact on the performance of the network. Designing a good MAC protocol thus can greatly determine the successful rate of operating a network.

2.1 Research Development Outline

Concerned about the research development of MAC protocols in WSN, main contributions can be divided as: MAC layer protocols' design and optimization [3][4][5][6], analysis and comparison of MAC protocols [7][8][9], cross-layer design between MAC layer and routing layer, or MAC layer and physical layer [10][11][12], design and research in IEEE 802.15.4 [13][14][15][16], as well as other potential applications [17][18].

Research in WSNs can be regarded as derivative and development from ad-hoc networks. Hence most MAC protocols in WSN are evolved from MAC protocols in wireless LANs and ad-hoc networks. However, WSN's own characteristics such as low-power, low processing and low storage capacity determine that its channel access method is different from most other wireless networks, which will inevitably lead to sacrificing some features to make up for its weakness.

Since WSNs have broad application prospects, to further develop this technology, in December 2000, IEEE 802.15.4 working group was founded, which is targeted at inexpensive applications among relatively simple devices (fixed, portable or mobile devices), which is emphasis on low-complex, low-cost, low-power and low-data-rate wireless connection technology. In December 2003, the first IEEE 802.15.4 standard is established, which specifies Physical Layer (PHY) and MAC layer for Low-Rate Wireless Personal Area Networks (LR-WPAN). Within just a few years since the publication of the standard, it has launched a wave on discussions and applications represented by Zigbee Alliance. Certain achievements have been realized on hardware architecture, operating system and application software-design based on this standard; some valuable test data have also been obtained in engineering applications of perspective discussions.

2.2 Important Indicators in WSN MAC Protocols

Since sensors in WSNs have very limited resources in energy, storage, computing capability and communication bandwidth, the function of a single node is weak, sensor networks' powerful function comes from many sensor nodes working corporately. Multi-point communications within local area would require MAC protocols to coordinate the wireless channel allocation. When designing a WSN MAC protocol, main considerations of performance indicators are the following: energy efficiency, network scalability, fairness, delay, bandwidth utilization and network throughput.

2.2.1 Energy Efficiency

Sensors may be placed in a dangerous environment or some places that are not easy to arrive by human beings. Recharging the batteries is usually impossible that sensors are thus with extremely limited energy supply. Therefore, as many discussions have shown, energy efficiency is the most notable feature to differentiate WSNs from other wireless networks. This feature is also the most important performance indicator in WSN.

Energy efficiency in WSNs is mainly aimed at terminal nodes in the network. In Deborah Estrin's special session report on Mobicom Conference, he pointed out that nodes consume the vast majority part of energy in wireless transceiver module built in nodes' hardware architecture [19]. Since MAC protocol directly controls the operation mode of transceiver modules, it is the most important factor that impact energy consumption, and once nodes' energy has been used out, the network will be declared as dead, so the designing of MAC layer protocols will directly influences the survival of network lifetime.

2.2.2 Network Scalability

Network scalability is another important indicator in WSNs. Ideal WSNs should have an intellectual ability to maintain the performance characters standing above the size and topology changing in the network.

Sensor nodes' large quantity, wide-spreading and directly facing specific applications decide the network have to change in the number of nodes or network topology from time to time. When the number and location of sensor nodes in the networks changed, MAC protocol should implement appropriate scalability support to the changes in network size, topology and density.

2.2.3 Fairness

This indicator reflects the capability that nodes or the application tasks in the network equitably sharing the channel.

In traditional user-oriented wireless communication networks, fairness means each user in the networks have equal right to send and receive data. In WSNs, however, fairness no longer simply means this, but rather refers to all nodes as a whole depending on communication tasks, which also determine this indicator's importance priority.

2.2.4 Delay

Delay signifies the time interval that successfully transmits a data packet from the transmitter to the receiver. WSNs are application-relevant networks. Various network transmission tasks in the network have different delay requirements.

2.2.5 Bandwidth Utilization

Utilization of network bandwidth reflects the channel usage condition in the network communication.

In other wireless networks, bandwidth utilization rate is a very important performance indicator, for example, in the networks such as cellular mobile communication systems and wireless local area networks (WLANs), channel bandwidth resource is so important that systems need to accommodate as many users as possible to deal with higher data rate's communication. Comparing with that, the quantity and data communication rate of nodes in WSNs is decided by application environments and network tasks, thus when designing network protocols for WSNs, bandwidth utilization is usually not the most important performance indicator.

2.2.6 Network Throughput

Researchers and engineers are frequently mentioned about network throughput, but there is not a unified accurate definition of this concept. In the research of MAC layer protocols, we explained the network throughput as: in a given time period, the effective data, which is the total data that the receiver successfully received minus the control information including frame's overhead, ACK, RTS/CTS, etc.

One thing worth to be mentioned, Of various network characteristics above, there will be some influence between each other, for example, fairness, delay and bandwidth utilization will all have an impact on network throughput. Of course, since WSNs are application-oriented network, to suit different needs of WSNs, there should be different network requirements, and thus the order of importance of these parameters should be decided by specific applications.

2.3 Energy Consumptions in WSN

Since energy consumption is the most important performance indicator in WSNs, before designing a MAC protocol for WSN, it is necessary to find and analyze the reasons that cause energy loss. Sensor nodes' ineffective energy consumption can be summarized as the following five areas: protocol overhead, collisions, overhearing, idle listening and load fluctuations.

2.3.1 Protocol Overhead

MAC protocol overhead is defined as MAC-related control packets and frames overhead that do not send effective data; such as RTS/CTS/ACK short packets as well as packet headers and trailers.

Energy consumption of protocol overhead is not useful for the users, if allocate too much channel bandwidth to them, the network will consume more energy. When the transmission contains only a few bytes of effective data, the cost of protocol will be too expensive.

2.3.2 Collisions

Collisions happen in the process of transmitting data, especially when a number of nodes send data in the channel at the same time, which leads to conflict among these data packets. Collisions only occur in contention-based MAC protocols that nodes compete to share wireless channels.

When more than one node sends their data packets to one single node at the same time, it is easy for such a situation to occur that two or more data packets arrive the same node at the same time. Along with this, signal interferences with each other will lead these collisions of data packets to be discarded, the receiver will not be able to receive the information accurately, which will lead to a waste of energy. Use RTS/CTS handshake mechanism can solve this problem, but it will require additional protocol overhead.

All MAC protocols need to consider collision avoidance. Collision problems are the main concerns in contention-based MAC protocols, while it generally is not an issue in schedule-based MAC protocols.

2.3.3 Overhearing

Overhearing means nodes receive and deal with unnecessary data information which is sent to other nodes.

Wireless medium is a broadcast medium, nodes share wireless channels and thus may be receiving and processing the data that is supposed to send to other nodes. Overhearing will lead to wireless receiver modules and processor modules consume more energy.

2.3.4 Idle Listening

Nodes do not know when their neighbor nodes will send data to them, so RF module has to remain in the receiving state and hence wastes a lot of energy.

Energy consumption in idle listening depends on hardware devices of wireless module and operation mode. For long-distance data transmission (0.5km and longer), node's transmitting power is far greater than the power used in receiving and listening. However, in short-distance wireless transmission modules, power consumes in listening, transmitting, and receiving are about the same order of magnitude, which is on average between 50-100%. Stemm and Katz measured "Wavelan wireless card" which works in 915 MHz, comparing the ratio of power consumption in listening, receiving and transmitting is about 1:1.05:1.4 [20], while for Digital IEEE 802.11/2Mbps wireless card, this ratio is about 1: 2:2.5 [21], Mica2 is about 1:1:1.41 [22].

Most sensor networks need to work for a very long time; in their work cycle, energy spends in idle listening will account for the majority part of total energy consumption.

2.3.5 Load Fluctuations

Load fluctuation means that network loads randomly change irregularly with the changes of users' needs, network communication condition, and so on.

Sudden increases of network load will increase the probability of collision. When the load gets close to the limit of channel capacity, which may lead to the collapse of the network, the channel will almost have no packets transmission, and cause the waste of a large amount of sending/receiving energy.

Energy consumption factors above are the key elements that should be of concern in designing MAC protocols. Some early works are all designed MAC protocols suitable for WSNs in different ways by adding dormancy mechanism. Many of the later jobs are on the basis of those papers, and make improvements and optimizations by considering the energy consumption factors above.

2.4 Classifications and Typical Algorithms of MAC Protocols

Until now, researches and developments in WSN MAC protocols have achieved numerous theoretical results. These researches designed and optimized MAC protocols in WSN from different perspectives. Along with current studies, the majority of scholars support the following four categories of classification:

1. Distributed/Centralized control: From the level of network structure;
2. Sharing a single channel/Multi-channel: From channel using in physical layer;
3. Fix allocated channel/Random access channel: From channel access mechanism;
4. Homogeneous/Heterogeneous structure: From the perspective of nodes.

In this paper, we use the third category of classification related to fix allocated and random access channels. MAC protocols in WSNs are divided into the following two categories:

(1) Random contention of wireless channel: contention-based MAC protocols;

(2) Non-contention, fixed channel allocation: schedule-based MAC protocols.

We sorted out some representative articles according to this kind of classification and described their basic algorithm ideas.

2.4.1 Contention-Based MAC Protocols

Contention-based MAC protocols have very good scalability, they are not only suitable for centralized networks, but also strongly adapt to real-time network topology adjustments in distributed network.

In contention-based MAC protocols, nodes compete for the channel by certain probability model, and transmit data if they successfully get the channel. Classic examples of such technologies include ALOHA [23] and CSMA (Carrier Sense Multiple Access) [24]. In ALOHA, nodes immediately transmit data packets through wireless channel after generating data (Pure ALOHA), or in the next available slot (Slotted

ALOHA). Once collision happened, nodes will repeat the competition process and re-transmit the data packet next time. In CSMA, before transmitting data packets, nodes will first listen to the channel and transmit data when the channel is idle.

Based on CSMA mechanism, the development of IEEE 802.11 [25] standard is so far the most widely used wireless network technology. IEEE 802.11 defines very specific rules for MAC layer's operational details, and the most famous one is wireless channel access method CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) mechanism among these rules. Represented by IEEE 802.11 standard, a number of wireless communication standards provide contention and non-contention (schedule) mechanisms. However, based on random access mechanism, collisions are inevitable in this kind of protocol and hence much energy is wasted on overhearing and retransmissions due to collisions. But in engineering applications, most manufacturers and entrepreneurs will still concern a lot about contention-based mechanism's low cost achievement, which they still consider it as the optimized plan.

2.4.1.1 WiseMAC

CSMA/CA mechanism has been widely applied in IEEE 802.11. However, the biggest disadvantage of contention-based mechanism is that idle listening wastes too much energy. In 2002, El-Hoiydi et al. [26] proposed a low energy carrier sense technology that periodically closed the radio frequency (RF) module, which is on the basis of non-persistent CSMA mechanism. When nodes have data to transmit, they begin sending data with preamble codes, which announce the receivers that there are data packets coming.

WiseMAC [27] is based on the preamble sampling technique above to lower the energy consumption in idle listening, and its central idea is by extending the time length of preamble, to transfer energy consumption from the receiver (high frequency) to the transmitter (low frequency). That is, the receiver periodically opens its RF receiving modules to detect whether there is a preamble signal. If there is a preamble signal detected, then it will keep listening until correctly receiving the entire information; if not, it continues to periodically close its RF modules and repeat the process. If the transmitters know the specific sampling schedule, it can then shorten the length of preamble. Based on this, while the set of node's sampling schedule is fixed, sending nodes can know the sampling schedule in advance; it then waits until the receiving node is about to sample and then sends the appropriate length of data packet preamble. By doing this, the time length of preamble can be shortened and the transmitters will save the energy. After sampling, the receiver will obtain shorter preamble, which also save the energy. WiseMAC protocol can automatically adjust the length of preamble to traffic load fluctuations: when the traffic load is low, long preamble is used while when the traffic load is high, short preamble is selected. Figure 2-1 shows the working mechanism of WiseMAC.

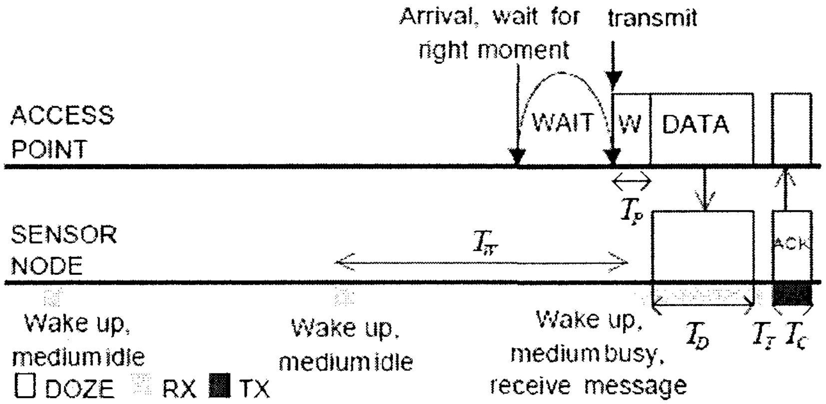


Figure 2-1 WiseMAC Working Mechanism

WiseMAC protocol does not need to establish a signal structure; it does not require the synchronization process among the nodes within the network and is adaptive to the traffic load. Through the experiment, it proved that energy consumption in WiseMAC protocol is small under low network traffic. However, for broadcast information, since source node need to consider all its neighbor nodes' sampling schedules, which requires long time length of preamble, which will affect its energy efficiency.

2.4.1.2 S-MAC

When discussing WSN MAC protocols, we have to consider S-MAC (Sensor-MAC) protocol [28]. It is one of the first proposed MAC protocols applied to WSNs. Starting from MAC layer, this protocol hands out a more complete description on technical challenges that sensor networks are facing and gives effective solutions. In the following years, S-MAC has greatly influenced contention-based MAC protocols, on the basis of which, a number of scholars and researchers have made revisions and perfections and gradually made it more mature. In the recent two years, S-MAC has emerged with engineering applications and today, a large number of academic papers and engineering data have proven that S-MAC is by far the most mature WSN MAC protocol. We will thus spend some time on this classic MAC protocol.

Although we classified S-MAC as contention-based protocol, evolved from classic contention avoid competition mechanism, S-MAC still adopts the thinking of time-slices (slots) to ensure sensor nodes' orderly dormancy. The length of time slot is determined by the application procedures, in the time slot, it is divided into working stage and dormancy stage. In 2002's first edition, the working stage is set as a fixed-length period. In order to better support data burst, in 2004 version, the length of working stage is adjustable within the time slot. Node in the dormancy stage turns its RF module off, main energy consumes in collecting and caching data. In the first working phase, nodes receive the synchronization information from their neighbors and store a schedule table of this information. After that, nodes build up the connection and begin the transmission through RTS/CTS/DATA/ACK handshake mechanism. This mechanism effectively reduces the energy waste caused by collision. Through synchronization information, adjacent nodes can adopt the same work/sleep strategy and new nodes can also join in. Such mechanism in the protocols is known as virtual cluster. SMAC protocol also used long message transmitting technology, which well supports long message transmissions.

For wireless channels, a large amount of theoretical analysis and simulation results have proven that transmission errors is proportional to packet length; that is, successfully transmitting rate of short packets is higher than long packets. According to this principle, long message transmitting technology divides long data information into a number of short information packets, by one time of RTS/CTS handshake, consecutive sending all the short packets in one time, which can improve the probability of successful transmission, and effectively reduce the control overhead.

Figure 2-2 below shows the communication interactions of S-MAC Protocol.

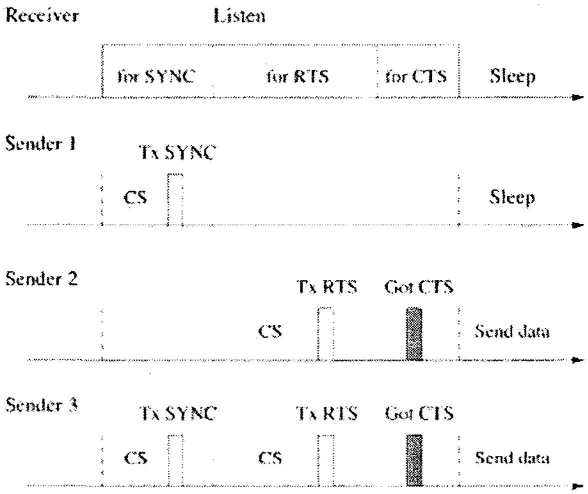


Figure 2-2 S-MAC Protocol Communications Interactive Diagrams

The advantage of SMAC protocol is its better expansion, which can well adapt to the changes of network topology; while its disadvantage is complex to achieve and occupies large storage space. This is especially prominent in resource-constrained sensor nodes.

2.4.1.3 T-MAC

Many protocols are developed on the basis of S-MAC, and they improved S-MAC from various angles, among which the most influential one is T-MAC protocol [29] (similar to the second version of S-MAC) and DMAC protocol.

T-MAC protocol considers idle listening as the main factor causing energy waste in MAC layer and it considers S-MAC spends a significant amount of energy on this; thus

T-MAC makes modifications on S-MAC's fixed length of listening period. It defines five activation events and defines non-active incident duration TA as signs of terminating the activation ahead of the schedule.

However T-MAC algorithm's idea about early terminates active nodes so that some nodes can enter dormancy earlier lead to another problem, that a number of nodes may miss some important RTS/CTS commands or communication appointments. T-MAC algorithm thus provides two ways to solve this early sleep issues: future request-to-send and taking priority of full buffers.

Figure 2-3 shows data interaction comparison of T-MAC and S-MAC.

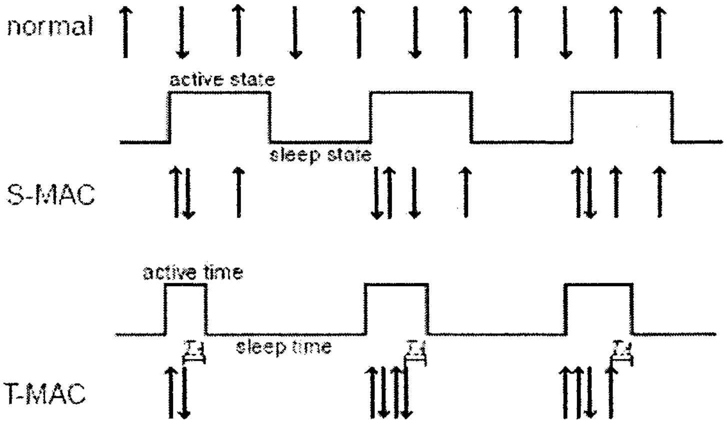


Figure 2-3 Data interactions in T-MAC protocol and S-MAC protocol

Despite improved from different perspectives of S-MAC, the algorithms and protocols are inevitable with certain technology trace of S-MAC since they are all on the basis of that. One of the most important features is that the entire network has to implement synchronization mechanisms. That is, in a time slot, all nodes wake-up at the same time, and nodes that have data packets to send begin to compete for the channel.

2.4.2 Schedule-Based MAC Protocols

Schedule-based MAC protocols allocate the channel before communication, it makes arrangement of channel access order by a reasonable way, so this is type of protocols does not experience collision problems as in contention-based mechanism. Scheduling mechanisms can be divided into FDMA/TDMA/CDMA (Frequency Division Multiple Access/Time Division Multiple Access/Code Division Multiple Access), as well as their hybrid methods.

The most widely used schedule-based MAC protocols for WSN is TDMA (Time Division Multiple Access). Many of the characters of TDMA are suitable for the energy-efficiency requirements in WSN. It does not have collision and retransmission problems which are suffered a lot in contention-based mechanisms; it is basically a kind of collision-free mechanism; according to the schedule table, nodes can enter the sleeping state in time to save the energy spending in long time of idle listening. It is an effective method in terms of energy-saving.

Almost all TDMA-based wireless sensor channel access technologies introduced sleeping mechanism to reduce energy consumption, meanwhile reduce the occurrence of overhearing and collisions. However, improving these performances come at the cost of information delay. As a sound WSN MAC protocol, it is not only providing a specific channel access mechanism, but also need to take further consideration of the important parameters such as energy-saving, network throughput and communication latency, etc. Existed mainstream TDMA-based algorithms are aimed at complex multi-hop distributed or hybrid network access mechanisms, slot allocation controls are usually too complicated as well as time slot length control algorithms. Taking into account the need to provide network infrastructure support for complex routing algorithm, the more comprehensive and reliable time division control mechanism, the more inevitably complex it is as well. To some extent, this disobeys the original intention of simplified protocols in WSN.

2.4.2.1 LMAC Protocol

LMAC protocol [30] belongs to contention-free mechanism. Unlike random access contention-based MAC protocols, LMAC uses a communication frame schedule strategy to deal with channel allocation, which well solves the problems of collisions and idle listening.

LMAC divided the channel into many time slots; each slot contains a control message and a fixed length data unit, and a number of time slots will form a fixed-length frame. LMAC's scheduling mechanism is simple that each active node controls one slot. If a node has data packets to transmit, it waits for its own time slot, and when the slot is coming, it first broadcasts a section of control message, announcing the receiver and transmitting packet length and then transmitting data the packet. If node receiving this control information is not the designated node, it will close its RF module to avoid overhearing. Different from other MAC protocols, after the receiver correctly receives the data packets, it does not send ACK information. LMAC leaves the reliability issue to higher-layer protocols. The method LMAC uses to avoid conflicts is through choosing the time slot that none of its two-jump-neighbor node occupies. The broadcasting information in control message contains a "bit-group" which has the slot occupied information of its one-jump-neighbor nodes. Newly joined nodes first listen to the control section to learn about which slot is idle and randomly select one to send their control information announcing the occupation of the slot. Other newly joined nodes hear that the slots are occupied; they'll have to be backoff and start again. Figure 2-4 shows an example about LMAC choosing the slots.

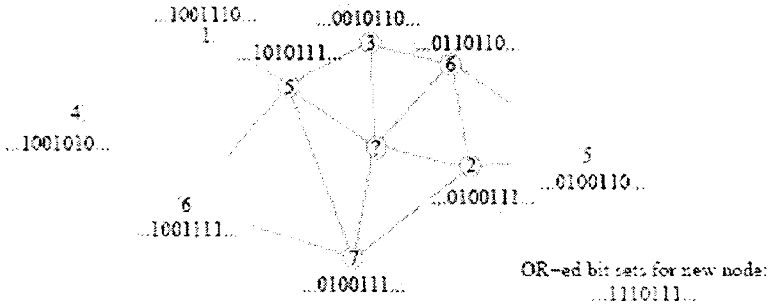


Figure 2-4 An Example for LMAC Choosing the Slots

The disadvantages of LMAC protocol are nodes must listen to the entire control section in the whole frame structure, even the slots that are not occupied. Since new nodes maybe join in at any time, and sensing for two-jump-neighbor node also increases the requirement of routing algorithm, which will increase the nodes' energy consumption and network expense.

2.4.2.2 BMA Protocol

BMA [31] is one of weighted types of MAC protocols based on TDMA. It developed and improved intra-cluster communication algorithm based on LEACH protocol's self-adapted clustering topology algorithm.

BMA protocol is divided into a cluster set-up phase and a stable-state phase. In cluster set-up phase, nodes elect the cluster-head according to how much energy is left. Then the cluster-heads elected broadcast their announcement in the clusters using non-persistent CSMA. All the other nodes will decide which cluster to join according to the strength of signal power it senses. Then, the system enters the stable-state phase which is made of a number of fixed-length sessions. Each session includes a contention period, a data transmission period and an idle period. Contention period also follows a schedule-based algorithm that all nodes open their RF modules and transmit a 1-bit control message to the cluster-head during its own assigned time slot if they had data to send. Afterwards, the cluster-head will aggregate the information and broadcast a scheduling strategy to the nodes within the clusters. Each node that has data to send will get a specific sending schedule. Nodes then will only open their RF modules during this time of period and process the transmission to the cluster-head. During other time periods, the nodes will fall asleep. If no nodes have data to send during the round, the length of the data transition period will be 0. After the cluster-head receives the data from nodes within its cluster, it will merge the data and forward them to the sink.

BMA shows the advantages of TDMA, which has better energy efficiency. When there are small amount of nodes in the network (i.e. when the network traffic is low), the network performance is especial ideal that the energy efficiency is observable and delay is relatively short, too.

2.4.3 IEEE 802.15.4 - Standard Can be Used for WSN

2.4.3.1 Overview

IEEE 802.15.4 [32] provides cheap equipment with low complexity, low-cost, low-power, low-data-rate wireless Internet standards. WSN is one of its main application areas. Like the majority IEEE standards, IEEE 802.15.4 defines the bottom two layer protocols: MAC (Media Access Control) layer and PHY (Physical Layer). IEEE 802.15.4 can be classified as beacon-enabled network and non beacon-enabled network.

2.4.3.2 None Beacon-Enabled Network

Although IEEE 802.15.4 uses CSMA/CA to access the channel, CSMA/CA in IEEE 802.15.4 possesses some different characteristics from IEEE 802.11, while for the main are still similar. In none beacon-enabled IEEE 802.15.4, they do not use superframe structure, in IEEE 802.15.4, it is called unslotted CSMA/CA, since only in superframe structure is there the concept of slot. At the beginning of the transmission, when there are data packets to be sent, the device needs to wait for a random time, if the channel is idle after that, nodes will send the transmitting requirements. If the channel is busy, then the equipment needs to wait for a random time again.

2.4.3.3 Beacon-Enabled Network

Beacon-enabled network divides time into a number of superframes; the superframe structure is shown below in Figure 2-5: the first part is CAP (Contention Access Period), the working mechanism of which is using slotted CSMA/CA; and the second part is CFP (Contention Free Period), which is left for GTS (Guaranteed Time Slots) transmission who has QoS requirements. Nodes reserve for GTS channel resource in CFP so they do not need to transmit data by CSMA/CA.

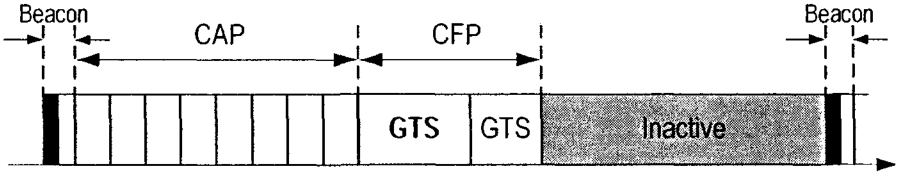


Figure 2-5 IEEE 802.15.4 Superframe Structure

Superframe is divided into 16 time slots including the beacon and superframe time, superframe duration and beacon interval (BI) are controlled according to the coordinator uses beacon order (BO) and superframe order (SO). Their relationship is as follows: $0 \leq SO \leq BO \leq 14$. This assures the superframe lasts no longer than BI. The beacon that the coordinator sends is not only using for synchronization purposes, but also contains other relative network information; superframes are classified by whether they use the reserving slots or not. With reserving slot, the superframe is divided into two parts: contention access period (CAP) and contention free period (CFP). Slots without reservation are all left to CAP. To save energy consumption, besides active parts, nodes in inactive parts are all in the sleeping state.

In contention phase, the coordinator broadcasts the beacon frame in the network. For nodes who wish to send data, they will send transmission requirements to the coordinator. Since wireless channels only allow one equipment send data at one time, all nodes who want to transmit data need to compete for the wireless channel using slotted CSMA/CA algorithm. Nodes first listen to the wireless channel to see whether it is used by other communicate links, if not, which means the channel is idle, then nodes will produce a backoff delay time to avoid the contention due to nodes may send data at the same time; if the channel is busy, the nodes then will keep on listening until the channel is idle and repeat the above slotted CSMA/CA competition.

2.5 Clustering Idea and Typical Algorithm for WSN

In WSN, sensor nodes' RF module consumes approximately the same energy in idle state as in the transceiver state, so only by closing nodes' communicate module can greatly decrease the energy consumption. Consider choosing certain nodes as the backbones according to some algorithms, we assume opening their communication module while closing none backbone nodes' communication module periodically, then the backbone nodes can form a connected network, which takes the responsibility as a routing of data transmission. This way not only ensures data communication within the original cover area, but also saves energy to a large extent. Such algorithm shows the idea of clustering; clustering algorithm divides the whole network area into numbers of connected sub areas; and nodes in the network can be classified as cluster-head and common nodes. Cluster-head are in charge of the common nodes around them within the cover area.

There are many advantages of clustering algorithm: cluster-head take the most responsibility of network communication and data management tasks. Comparing to pure distributed algorithm, clustering algorithm greatly facilitates the network transmission pressure due to the complex routing system; since most nodes close their communication modules in a relative long time, the whole network life period will be prolonged significantly; etc. Various advantages of clustering algorithm make this strategy as one of the most important network topology management methods. The most famous clustering algorithm is from MIT's μ-Adaptive Multi-Domain Power Aware Sensors (uAMPS) Project called Low-Energy Adaptive Clustering Hierarchy (LEACH) Protocol [33].

LEACH protocol randomly rotates the cluster-head to distribute the energy consumption evenly among all sensors in the network [34]. The operation of LEACH is separated into rounds. Each round consists of a set-up phase and a steady-state phase. When the set-up phase begins, each node must make a decision about whether to be a cluster-head based on certain algorithms. The new cluster-head then broadcasts the advertising message to the other nodes and claim that it is the cluster-head by using a non-persistent CSMA. Each non-cluster-head node then decides which cluster to join by communicating with which cluster-head requires the minimum amount of energy. Once the clusters are built-up, the system enters into steady-state phase.

During the steady-state phase, each non-cluster-head node sends its data to the cluster-head during its allocated transmission slot. The radio of non-cluster-head node is turned off except for its transmission slot. The cluster-head then sends the aggregated and compressed data to the base station. This process is repeated every time of the round until time interval expires.

LEACH applies direct-sequence spread spectrum technique to reduce inter-cluster interference. All nodes within a cluster will communicate with the cluster-head using a unique spreading code.

LEACH does a good job in topology management of distributed networks and node's clustering tasks, it is an efficient clustering algorithm. However, for intra-cluster algorithm, it just mentioned simply that it took TDMA as its MAC protocol, which is based on the assumption that system always has data to transmit. TDMA do have a lot of advantages in this kind of conventional time-regular monitoring tasks, which is especially common in the situation such as wireless data transmission/access network which is mainly concentrated in video and data services. However, when there is some emergency happened, since its schedule table is defined in advance, TDMA is then not as flexible and efficiency to these sudden changes. And this is quite possible in WSN such as eventdriven nodes send the alarm information about the emergent affairs. In a word, using TDMA as MAC protocol is not as flexible in network resource allocation and lack of real-time response to some emergent events. In this paper, we take the clustering idea of LEACH to organize a WSN distributed network. Based on this and corporate with the advantages of contention access and scheduled data transmission, we proposed a new intra-cluster MAC protocol, which is described in detail in the following chapter.

CHAPTER 3

CONTENTION RESERVE ALGRITHM AND ENERGY CONSUMPTION ANALYSIS

3.1 Idea for Protocol Design

According to the analysis of various MAC protocols in WSN, as well as the research of IEEE 802.15.4 and MAC layer's design requirements of WSN, in this thesis, we propose an intra-cluster, contention reserved MAC protocol (CRMAC) for WSN. CRMAC combines the specific characteristics of contention-based and schedule-based MAC protocols, which effectively connects free contention mechanism and slot allocation together. This protocol can be applied to WSN to use the resource more efficiently, which means to perform better in system delay and throughput under low energy consumption.

3.2 Protocol Description

As in LEACH, which is mentioned above, CRMAC is also a cluster-based algorithm, communication operation is divided into rounds, each round consists of a set-up phase and several superframes, which are further divided into three steps, namely slot reserve step, schedule assigned step, and guaranteed data transmission step.

The structure of each round is shown below in Figure 3-1,

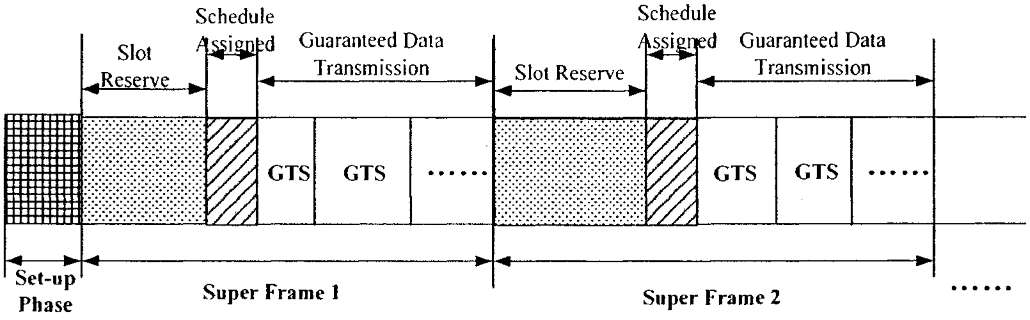


Figure 3-1 CRMAC Structure

3.2.1 Set-up Phase

Nodes in the network form the clusters and elected the cluster-head by certain algorithm in this step. We assume there are n+1 nodes within one cluster and one of them acts as cluster-head. Clustering algorithm can be some mature protocol, here we choose LEACH: the best node is selected as the cluster-head from randomized rotation among the same structure sensors to avoid draining the battery of any particular sensor in the network. Then the selected cluster-head in this round will broadcast an announcement to the other sensor nodes within the cluster area. Nodes that receive this announcement will join the cluster accordingly. Of course, if the structure includes powerful nodes, such as FFD (Full Function Device) in IEEE 802.15.4 as organizers, then we do not need to elect the cluster-head and will hence jump directly to the next phase.

3.2.2 Superframe

After the cluster is set-up, the entire network should be in a steady state, which is made of several superframes. Each superframe in CRMAC has three steps: slot reserve step, schedule assigned step, and guaranteed data transmission step.

3.2.2.1 Slot Reserve Step

In this step, cluster-head collects information from non-cluster-head nodes that have data to send. These nodes must apply for the slots to transmit data. Slots are set as the same length. In this step, all nodes are kept awake and they use CSMA to communicate with the cluster-head, once nodes get the channel, they immediately send a short packet, which contains the slot reserving information showing data transmission request, packet size, etc. By the end of this step, the cluster-head will form a schedule table based on this information.

We define fixed time length for slot reserving and once the time is out, nodes that do not make the appointments will lose the chance of transmitting data in this superframe. This can ensure that when using CSMA to compete for the channel, sensors will not waste too much time. Since CSMA is a contention-based mechanism, when too many nodes have data to send in one cluster, it is quite possible that some nodes will not have enough time to send their reserved data packets.

In CRMAC, we choose CSMA instead of slotted CSMA/CA, this is because compared to data packets, the length of reserving packets is much shorter, if we send these short reserving packets using slotted CSMA/CA like IEEE 802.15.4 does, time occupation rate in the wireless channel will be much lower and waste more energy. Besides, since the probability of collisions happened in transmitting shorter packets in the channel is much smaller, CTS/RTS is not necessary, which will waste extra energy consumption on overhead and decrease the throughput.

3.2.2.2 Schedule Assigned Step

After slot reserve, the cluster-head should already have learned about the communication information of the nodes within the cluster. So now the cluster-head aggregates the information and broadcasts the schedule table within the cluster. The cluster-head will also process the synchronization task in this step to make sure that at the end of this step, all nodes have the same schedule table.

3.2.2.3 Guaranteed Data Transmission Step

In the following step, nodes only need to transmit data exactly according to the schedule table. Here, the communication is entirely contention-free TDMA mechanism: meaning that in any specific slot, only the owner of the slot can use the channel to communicate with the cluster-head and transmit data, while all of the other nodes will fall asleep.

Here we need to pay attention: in IEEE 802.15.4 standard, it defines the length of each GTS as the integer times of the slot. While it is different in CRMAC, the length of each GTS is different, and it may not be the integer times of the slot. Nodes hand up communication requirements according to its information amount, which the cluster-head will allocate the time resource based on that. This way of allocation defined time length based on the information amount while in IEEE 802.15.4, it is defined by the slots.

3.3 Energy Consumption Analysis

Energy consumption is one of the most important parameters to distinguish wireless sensor networks from other wireless communication networks. In this chapter, we will model and analyze the energy consumption on CRMAC protocol.

For the convenience of analysis, we repeat the assumptions above: assume there are n+1 nodes within a cluster and one is act as the cluster-head and the other n nodes will be non-cluster-head nodes which is called common nodes for short; n_i out of these n nodes in the i_{th} superframe that have data to transmit; energy consumed in data transmitting, data receiving and idle listening are E_{tx}, E_{rx}, E_{id}, accordingly; system defines the length of the broadcast frame is L_b, the length of data packet is L_d; and sensors RF module transmission rate is R.

3.3.1 Slot Reserve Step

3.3.1.1 CSMA/CA Mechanism Analysis

Contention reserve step uses random contention access mechanism. To analyze the energy consumption in this phase, let us first review the operation principle of Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA):

Nodes transmit packets after detecting the channel is idle for more than a specified time, which is called Distributed Inter Frame Space (DIFS); if the channel is busy, the nodes will wait until the channel is idle for DIFS, and then randomly choose a backoff delay, start up the backoff counter and transmit packet after the backoff delay. The backoff counter will decrease by time when the channel is idle, while stop when the channel is busy and resume until the channel is idle for DIFS again; when the backoff counter decrease to 0, and nodes begin to transmit the packets. The backoff process is shown below in Figure 3-2:

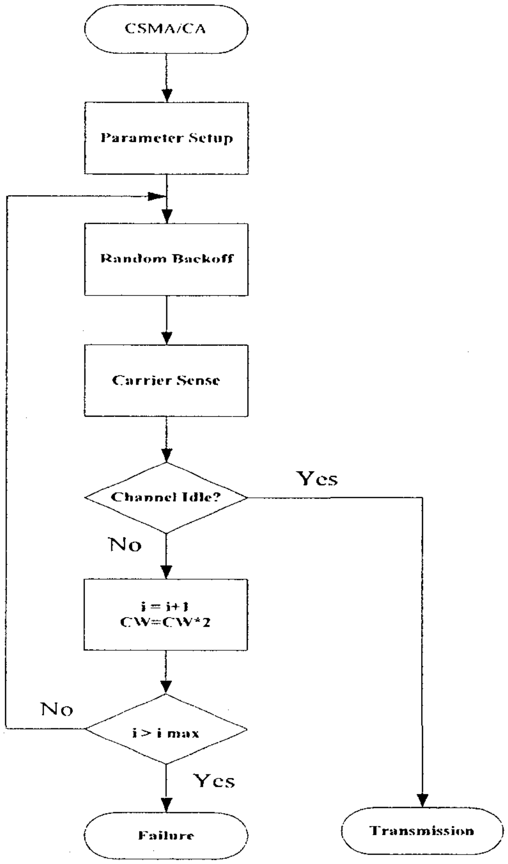


Figure 3-2 Backoff Working Process of CSMA/CA

Backoff interval is randomly selected according to uniform distribution between discrete intervals [0, CW). CW (Contention Window) defines the length of backoff delay time. We need to point out two important parameters here: BE and NB. BE (Backoff Exponent), is a parameter related to CW, which will influence the length of backoff delay time, given CW= 2^{BE}. The definition of BE maximum needs to consider the influence of overall system efficiency. NB (Number of Backoff Times), its original value is 0, when nodes want to transmit data, it will first wait for a period of backoff delay time. If they detect the channel is still busy, then they will repeat the backoff time step, and the value of NB will add 1. After sensor nodes listen to the channel until the maximum of NB times, if the channel is still busy, it will discard this transmission to avoid too much overhead.

3.3.1.2 Discrete-Time Markov Chain Model

Transmitting process can be either successful or fail. Let the stochastic process $B(t)$ represent the backoff counter. Discrete time t and $t+1$ represent two consecutive slot times T_{slot}, which corresponds to the records in the backoff time counter. The relationship between the backoff windows is defined as: $W_o = CW_{\min}$, $CW_{\min}$ is the minimum contention window, and also the initial value of CW. Each failed transmission will double the value of CW and repeat the contention access process above until it succeeds or attains maximum value of CW. The minimum and maximum contention windows are both decided by the characteristics of physical layer. When getting the BE^{th} times of retransmission, $CW = 2^{BE} W_o$.

Let the stochastic process $S(t)$ represents the backoff state (0, 1, ... , m, m is the maximum backoff state) of the station at time t. Here, we assume no matter at which retransmissions, each packet's failed transmitting probability p is constant and independent. Thus stochastic process $\{ S(t), B(t) \}$ stands for nodes' backoff process and can be represented by discrete-time Markov chain shown below in Figure 3-3.

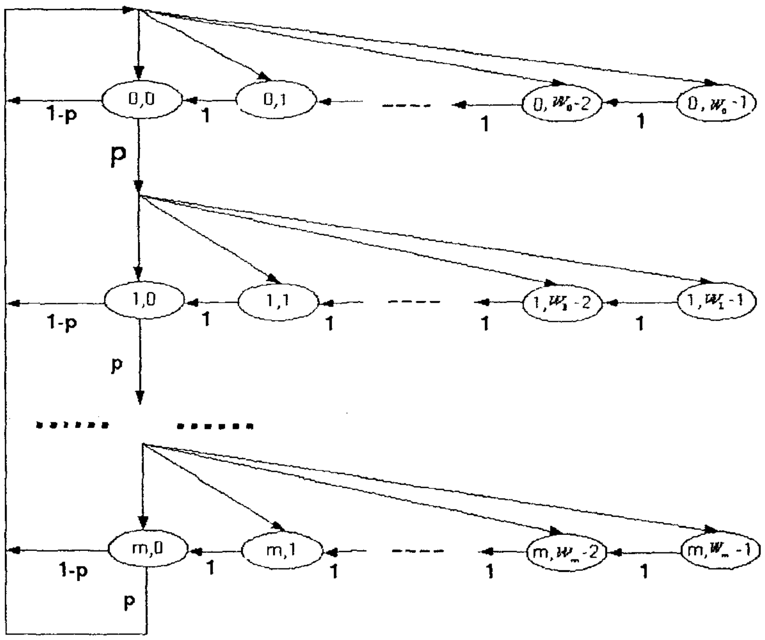


Figure 3-3 Markov Chain Model

Below is a simple description of Markov chain model. First, we analyze the figure above of 2-dimantional stochastic process $\{S(t), B(t)\}$, its single-step transfer probability is as follows:

$$P\{b_{i,j}/b_{i,j+1}\}=1, \quad i\in(0,m), \quad j\in(0,W_i-2) \tag{1}$$

$$P\{b_{i,j}/b_{i-1,0}\}=\frac{p}{W_i}, \quad i\in(1,m), \quad j\in(0,W_i-1) \tag{2}$$

$$P\{b_{0,j}/b_{i,0}\}=\frac{1-p}{W_0}, \quad i\in(0,m-1), \quad j\in(0,W_0-1) \tag{3}$$

$$P\{b_{0,j}/b_{m,0}\}=\frac{1}{W_0}, \quad j\in(0,W_0-1) \tag{4}$$

Here, $b_{i,j}=\lim_{t\to\infty}P_r\{S(t)=i, B(t)=j\}, i\in(0,m), k\in(0,W_i-1)$, represents the stationary distribution of Markov Chain.

The meanings of formulas above are listed as follows:

Eq (1) means that backoff time counter will minus 1 each time;

Eq (2) means if collision happens at backoff stage i-1, then the backoff stage will add 1, and randomly re-select a new backoff window between(0, W_i-1);

Eq (3) means after backoff stage i's backoff waiting time decreases to 0, it will compete the channel again and successful, then the backoff window will restart from the beginning.

Eq (4) means that when BE attains the maximum value, if the competition succeeds, backoff window will restart from the beginning. If collision happens, then it will announce failure of this time of transmission and reset the backoff window.

Assume this Markov chain model has stationary distribution and define this distribution as $b_{i,j}$, we get the state transfer relationship:

$$b_{i,0} = p^i b_{0,0}, \quad i \in (0,m)$$

$$b_{0,j} = \frac{(W_0 - j)}{W_0}[(1-p)(b_{0,0} + b_{1,0} + \cdots + b_{m-1,0}) + b_{m,0}], \quad j \in (0, W_0 - 1)$$

$$b_{i,j} = \frac{(W_i - j)p}{W_i} b_{i-1,0}, \quad i \in (0,m], \quad j \in (0, W_i - 1)$$

$$\sum_{i=0}^{m} \sum_{j=0}^{W_i - 1} b_{i,j} = 1$$

Through these simultaneous equations, we get the state transfer probability matrix of backoff window in contention reserve step:

$$\begin{pmatrix} b_{0,0} & \frac{(W_0-1)}{W_0}b_{0,0} & \frac{(W_0-2)}{W_0}b_{0,0} & \cdots \frac{1}{W_0}b_{0,0} & & & & \\ pb_{0,0} & \frac{(W_1-1)p}{W_1}b_{0,0} & \frac{(W_1-2)p}{W_1}b_{0,0} & \cdots \ \cdots & \frac{p}{W_1}b_{0,0} & & & \\ p^2b_{0,0} & \frac{(W_2-1)p^2}{W_2}b_{0,0} & \frac{(W_2-2)p^2}{W_2}b_{0,0} & \cdots \ \cdots & \cdots & \frac{p^2}{W_2}b_{0,0} & & \\ \vdots & \vdots & \vdots & & & \ddots & & \\ p^{m-1}b_{0,0} & \frac{(W_{m-1}-1)p^{m-1}}{W_{m-1}}b_{0,0} & \frac{(W_{m-1}-2)p^{m-1}}{W_{m-1}}b_{0,0} & \cdots \ \cdots & \cdots & \cdots & \cdots \frac{p^{m-1}}{W_{m-1}}b_{0,0} & \\ p^mb_{0,0} & \frac{(W_m-1)p^m}{W_m}b_{0,0} & \frac{(W_m-2)p^m}{W_m}b_{0,0} & \cdots \ \cdots & \cdots & \cdots \ \cdots & \cdots & \frac{p^m}{W_m}b_{0,0} \end{pmatrix}$$

This is a matrix that about $b_{0.0}$, to solve $\sum_{i=0}^{m}\sum_{j=0}^{W_i-1} b_{i,j}$, observe its coefficients:

Add up the 1st row of coefficients: $1+(1-\frac{1}{W_0})+(1-\frac{2}{W_0})\cdots+(1-\frac{W_0-1}{W_0})=\frac{W_0+1}{2}$

Add up the 2nd row: $[1+(1-\frac{1}{W_1})+(1-\frac{2}{W_1})\cdots+(1-\frac{W_1-1}{W_1})]p=\frac{W_1+1}{2}p$

……

Add up the $(m+1)^{th}$ row: $[1+(1-\frac{1}{W_m})+(1-\frac{2}{W_m})\cdots+(1-\frac{W_m-1}{W_m})]p^m=\frac{W_m+1}{2}p^m$

According to the increasing rules of backoff window, we have $W_i=2^iW_0$, so the sum coefficients of (m+1) rows are:

$$\frac{1}{2}[(W_0+2W_0p+\cdots+2^mW_0p^m)+(1+p+p^2+\cdots+p^m)]=\frac{1}{2}[W_0\frac{1-(2p)^{(m+1)}}{1-2p}+\frac{1-p^{m+1}}{1-p}]$$

$$\sum_{i=0}^{m}\sum_{j=0}^{W_i-1} b_{i,j}=\frac{1}{2}[W_0\frac{1-(2p)^{(m+1)}}{1-2p}+\frac{1-p^{m+1}}{1-p}]b_{0,0}=1$$

Thus, $$b_{0,0}=\frac{2(1-p)(1-2p)}{W_0(1-p)[1-(2p)^{m+1}]+(1-2p)(1-p^{m+1})}$$

3.3.1.3 Energy Consumption Analysis in Slot Reserve Step

After the analysis above about Markov Chain Model of contention access mechanism, we now further analyze the energy consumption of CRMAC model.

Assume the stationary random probability of a node transmits a packet at a random time is**Error! Bookmark not defined.** τ, time length in contention reserve step is T_c, let p_{tx} be the probability of system have packets to send at any given time (i.e. the probability that there is at least one reserving message sending in any designated time slot, and also the channel has only one node that transmits the data at that time slot.). One thing should be pay attention that this probability is different from τ , which stands for the probability that "just one" node has packet to transmit, thus,

$$p_{tx} = 1 - (1 - \tau)^n$$

and we have,

$$p = 1 - (1 - \tau)^{n-1}$$

After defining p_{tx}, we can define the probability of successfully transmitting a reserving request; that is, the probability of no collision occurred in the channel - p_s:

$$p_s \times p_{tx} = C_n^1 \tau (1 - \tau)^{n-1} \Rightarrow p_s = \frac{n\tau(1-\tau)^{n-1}}{p_{tx}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}$$

And τ is defined as follows: $$\tau = \frac{\sum_{i=0}^{m} b_{i,0}}{\sum_{i=0}^{m} \sum_{j=0}^{W_i - 1} b_{i,j}}$$

Bring $b_{0,0}$ into τ ,

$$\tau = \frac{\sum_{i=0}^{m} b_{i,0}}{\sum_{i=0}^{m}\sum_{j=0}^{W_i-1} b_{i,j}} = \sum_{i=0}^{m} b_{i,0} = (1+p+p^2 \cdots + p^m)b_{0,0} = \frac{1-p^{m+1}}{1-p} b_{0,0}$$

$$= \frac{2(1-2p)(1-p^{m+1})}{W_0[1-(2p)^{m+1}](1-p)+(1-p^{m+1})(1-2p)}$$

Bring the parameters of IEEE 802.11 into the function, which the length of minimum contention window is 31. So,

$$\tau = \frac{2}{31} \frac{1}{1+\frac{[1-(2p)^{m+1}](1-p)}{(1-2p)(1-p^{m+1})}}$$

Thus at contention access step, the energy consumption $E_{reserve}$ is,

$$E_{reserve} = T_c \times p_s \times P_{tx}$$

3.3.2 Energy Consumption in Schedule Assigned Step

Energy consumption for cluster-head is to broadcast the schedule table, while for common nodes is to receive this schedule table. So energy consumption in this step is:

$$E_{sch} = P_{tx} \times \frac{L_b}{R} + P_{rx} \times \frac{L_b}{R} \times n$$

3.3.3 Energy Consumption in Guaranteed Data Transmission Step

Energy consumption for common nodes in guaranteed data transmission step is:

$$E'_{GTS} = P_{tx} \times \frac{L_d}{R}$$

For cluster-head, it is receiving data at the same time when common nodes transmitting data, thus system energy consumption in this step is:

$$E_{GTS} = (P_{tx} + P_{rx}) \times \frac{L_d}{R} \times n_i$$

3.3.4 System Energy Consumption

From CRMAC's working mechanism, nodes' total energy consumption E in a superframe is,

$$E = E_{reserve} + E_{sch} + E_{GTS}$$

$E_{reserve}$: Energy consumption in slot reserve step;

E_{sch}: Energy consumption in schedule assigned step;

E_{GTS}: Energy consumption in guaranteed data transmission step.

CHAPTER 4

SIMULATION

In this chapter, we use system-level simulation software OPNET and NS-2 to model and simulate CRMAC protocol as well as evaluate its performance.

4.1 Introduction of Simulation Tools

Network simulation is a method to reflect the real network environments by building a virtual environment in the computer. It imitates network activities in the reality through mathematical or dynamic Monte Carlo algorithm, which can effectively improve the network plan as well as design reliability and accuracy.

4.1.1 Introduction of OPNET Modeler

OPNET [35] processes the network activities by a three-layer model, that is, network model, node model and process model. Its wireless model is based on pipeline stage architecture to determine the connections and communications between nodes;

users can specify the frequency, bandwidth, power and other features including antenna gain modes and terrain model. OPNET is suitable for simulating large scale networks; it provides many protocol modules from physical layer to application layer, including free space communication, IEEE 802.11, TCP/IP, etc.

OPNET possesses many advantages such as modular, hierarchical, flexible and changeable in network scene setting, convenient and intuitive in simulation results analyzing. It can simulate the networks that are very complicated in the reality, and now it has become the most popular large-scale network simulation software. It has friendly user interface and can be used conveniently under Windows; the simulation speed is fast in OPNET and very easy to spread the network; it also has the interface to Microsoft Excel which can facilitate the data extraction and process of the simulation. The disadvantage of OPNET is: for the modules that do not exist in OPNET, the simulation programmers have to create the simulation according to the protocol needed and model it using the three-layer model: process-node-network. If the protocol is complicated, the work load of coding to achieve the process model may be much too enormous.

4.1.2 Introduction of NS-2

NS-2 (Network Simulator 2) is a famous discrete event simulation tool for network research. It contains numerous network protocols, schedulers and tools that are used for the simulations such as TCP protocols, routing algorithms, multi-broadcasting protocols, which are processed through wired or wireless, local or satellite connections. NS-2 mainly applies itself in simulating OSI (Open System Interconnection) models; it can trace the simulations in detail and uses Network Animator (NAM) to playback. NS-2 use

C++ and OTCL to write the programming code: to accomplish the module by C++, and to build the simulation environment by OTCL.

NS-2 [36] [37] is a kind of open source software, which provides free download, and this is the biggest advantage of NS-2. Many research groups make expansion on it and write large quantities of various protocols' source code as well as share them. For example, in WSN simulations, the newest NS-2 version contains so many modules such as sensor model, battery model, tiny protocol stack, hybrid simulation support and scene tools, etc; source code that has already been developed including IEEE 802.15.4, LEACH, S-MAC, etc. However, since NS-2 processes very detailed simulations to data packet level, close to the quantity of real processing data packets, it restricts itself from performing large-scale network simulation. Besides, it is not so independent among NS-2's different modules that a small change in C++ source code will force re-compilation of the whole program; it only supports Linux system which makes the user interface not as friendly; using two programming languages C++ and OTCL makes the simulation program more complex; these make NS-2 not as easy to use.

4.1.3 Simulation Tools Selection

CRMAC Protocol that we proposed in this thesis contains two types of wireless access mechanisms, that is, contention phase and schedule phase, in contention access phase, we use IEEE 802.11-like protocol, while data transmission phase we still use schedule access mechanism.

Generally speaking, IEEE 802.11 is hard to achieve in NS-2 while has a quite easy and complete protocol model in OPNET, we only need to modify the existing module and can simulate the contention phase of our protocol. Meanwhile, developed on the basis of NS-2, LEACH protocol packet contains complete clustering algorithm and pure TDMA schedule mechanism, which can perfectly perform the network simulation in data transmission phase of CRMAC. Thus, in this chapter, we will first use OPNET to carry out the simulation for contention phase and set the results as the entry parameters to NS-2, which processes the simulation in contention-free phase, and finally get the overall simulation curve to complete the entire CRMAC protocol simulations and evaluations.

4.2 Modeling in Slot Reserve Step

According to the analyses above, this part of simulation will be designed and possessed by OPNET. Through OPNET, we will get the following parameters, which can be supplied to NS-2 as entry parameters:

1. When upper-layer's data packet size is fixed, the relationship among re-transmission times, contention time period and contention successful probability;
2. Under certain re-transmission times and contention time, the throughput of the network;
3. The relationship between contention time length and energy consumption.

4.2.1 Modeling

4.2.1.1 Network Model

To make sure the comparison and analysis are done under the same condition, we apply the same network model to IEEE 802.15.4 and CRMAC. The network topology is shown as below in Figure 4-1. Assume a clustered network has already built. 20 nodes in one cluster are randomly spread in a 10m by 10m bounded area. A central access node act as a cluster-head is placed randomly in the area and source node will transmit data to the cluster-head directly. Wireless sensors will compete to transmit data at the same time.

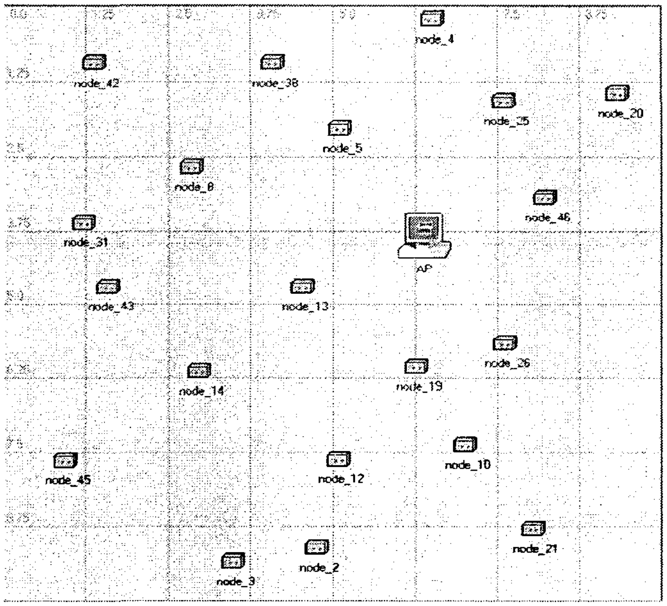


Figure 4-1 Network Model

4.2.1.2 Node Model

IEEE 802.15.4 and CRMAC use the same node model, which is shown below in Figure 4-2.

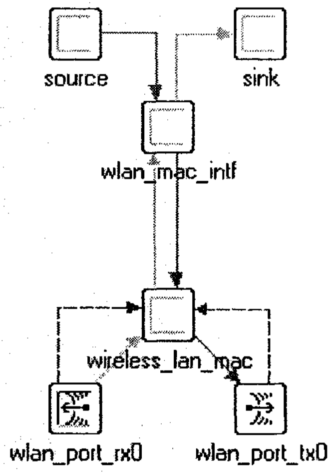


Figure 4-2 Node Model

Node model are divided into 4 modules, which are, source module, sink module, wlan_mac_intf module and wireless_lan_mac module. Their specific roles are:

1) Source. For common sensor nodes, this mode is used for producing traffic source; the data packets it produced will be launched to lower layer, and send out using contention-based mechanism. For central nodes, this module does not have effect at this scene.

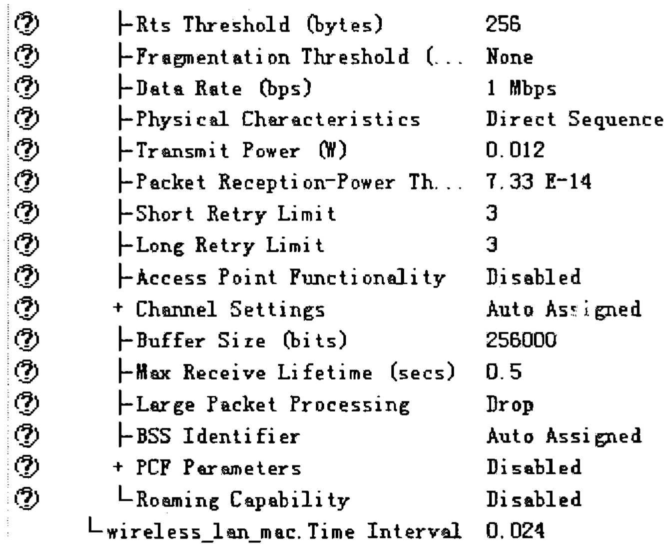
2) Sink. For central nodes, all useful data receiving from lower layer will forward to this module. For common sensor nodes, this module does not have effect at this scene.

3) Wlan_mac_intf. Adapt the packet format between upper layer and lower layer.

4) Wireless_lan_mac. This is the core module which realizes all the protocols in MAC layer; it mainly assures credibility data transmitting and receiving in data link layer. This module takes IEEE 802.11 as the principle.

5) Transmitter and receiver. The power of transmitter and receiver is set as 12mW [37], When nodes are at sleep state, energy consumption is low which only need to maintain basic computing operation in CPU, in this simulation, power consumption in sleep state is set a typical value of 1mW [37].

To control the nodes more conveniently, we add wireless_lan_mac time interval attribute in sensor nodes, this attribute is the longest time of contention period and its unit is second, it acts as the timer in the network. Once the time is out, contention period will be finished. Different setting of this time interval attribute and re-transmission times will lead to different successful probability in contention phase. Parameters setting examples are shown below in Figure 4-3:



├Rts Threshold (bytes)	256
├Fragmentation Threshold (...	None
├Data Rate (bps)	1 Mbps
├Physical Characteristics	Direct Sequence
├Transmit Power (W)	0.012
├Packet Reception-Power Th...	7.33 E-14
├Short Retry Limit	3
├Long Retry Limit	3
├Access Point Functionality	Disabled
+ Channel Settings	Auto Assigned
├Buffer Size (bits)	256000
├Max Receive Lifetime (secs)	0.5
├Large Packet Processing	Drop
├BSS Identifier	Auto Assigned
+ PCF Parameters	Disabled
└Roaming Capability	Disabled
└wireless_lan_mac.Time Interval	0.024

Figure 4-3 Node's Attribute Settings

4.2.1.3 MAC Process Model

In contention access step, IEEE 802.15.4 and CRMAC have similar process model. Assume upper-layer's module produces data packets with a relative long time interval (>

Time Interval), which can avoid dealing with more than one packet within one time interval. So when MAC layer processes data packets within the time intervals, if data packet is not transmitted successfully and meanwhile it does not obtain the re-transmission threshold, the system will keep trying, or else, it will stop.

MAC layer protocol for this part is based on IEEE 802.11 protocol model and modified on it, which the figure is shown below in Figure 4-4. We add certain state transfer conditions based on IEEE 802.11's original state transfer model, since when the timer is over, the process may be in any state, by adding new transfer conditions, we can make sure no matter which state that the Finite State Machine (FSM) is in, it will all jump back to the state IDLE when the time interval slot arrives. Detail explanation is as follows:

1) DEFER → IDLE. Transfer condition – the timer is over.
2) WAIT_FOR_RESPONSE → IDLE. Transfer condition – the timer is over.
3) BACKOFF → IDLE. Transfer condition – the timer is over.
4) TRANSMIT → IDLE. Add a judgment condition on original BACK_TO_IDLE transfer condition. That is, under the original condition, if the timer is over, it also needs to send the state transfer from transmit to idle.

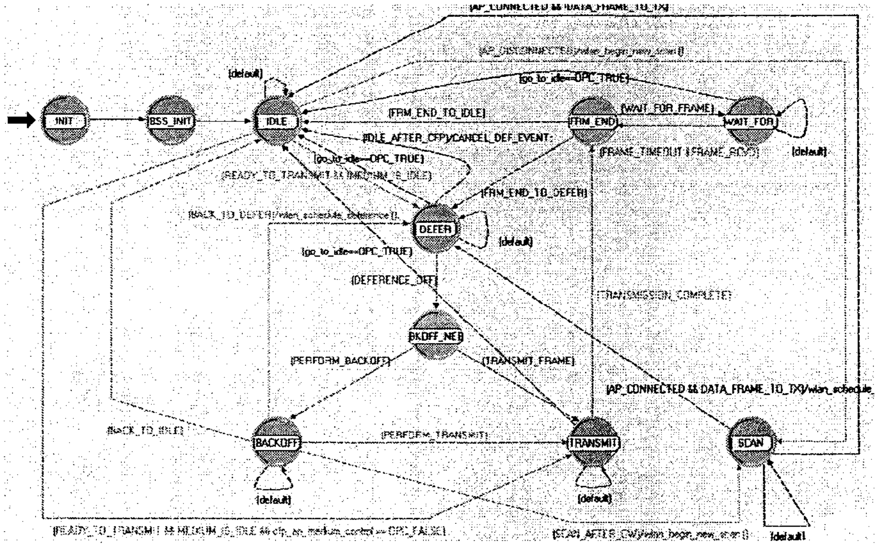


Figure 4-4 Process Model

4.2.1.4 Data Source Process Model

There are some differences here with data source model between CRMAC and IEEE 802.15.4.

1) CRMAC

In contention reserve step, CRMAC only sends reserve packets instead of data frame. Change the configuration of data source to make it produce a 32bit reserve application packet per 0.3s, thus traffic load in MAC layer is

$$\frac{32bit}{0.3s} = 106.67bit/s$$

Since in this step, packets' size is relatively small, we adopt the way of directly transmit the packets which neglect the interactive of RTS and CTS. However, the receiver (cluster-head) still needs to send acknowledgement (ACK). We simplified the structure of ACK and reduce its length to 16bits for this application scene according to our design principle that using short packets to decrease the expense.

2) IEEE 802.15.4

IEEE 802.15.4 also needs to send reserving packets. The configuration of the size of reserving packets is set the same as CRMAC.

According to the standard of IEEE 802.15.4, assume 5 out of 20 nodes will apply for CFP slots in during CAP; only the first 2 will successfully get the permission and send data in CFP the following round. The other nodes will then still have to compete for the channel and send data in CAP.

4.2.2 Simulation and Theoretical Data Analysis

In this simulation, physical layer's transmission rate is 1Mbit/s, set one slot as 5ms (time needed for transmitting 625 byte.)

4.2.2.1 CRMAC

1) Simulation and Results

Changing different configurations of attribute value, we can obtain different data dropped rate in the network and thus get successful frame transmitting probability. The figure below shows the data when we set time intervals as 10ms, and re-transmission times as 3; the average data dropped rate is about 832.1bits/s. Figure 4-5 shows the detail simulation data.

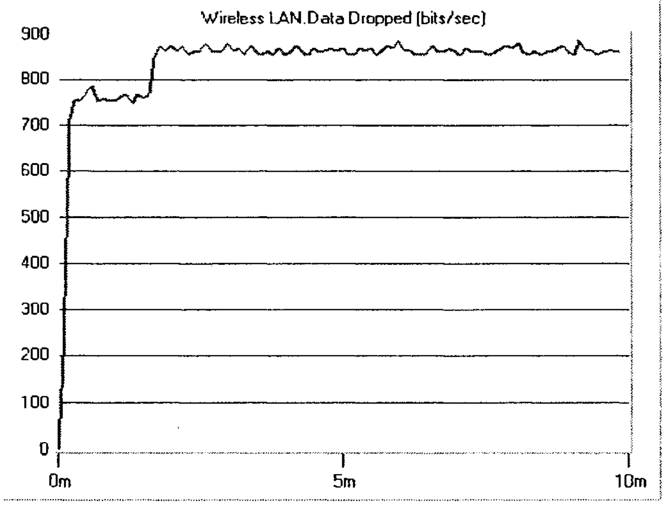


Figure 4-5 Average Data Dropped Rate Simulation

By this way and changing the number of re-transmission times and Time Interval, we obtain more simulation data as shown below.

In order to get the best attribute settings in this simulation, we repeat the simulation experiments for many times, Table 4-1 below is the comparison of simulation experiment results. In which the objects in bold letters means the shortest time needed for the system arriving the steady-state, and successful access probability is the biggest at this time. Although the longer time spends, the bigger the contention successful probability, it will cost energy waste meanwhile. The two elements need to be compromised.

Table 4-1 Re-transmission Time VS. Contention Access Rate

Num of Retransmission	Contention Period (ms)	Ratio of Success (%)
2	8	63.0276
2	9	71.2336
2	***10***	***74.3808***
2	14	74.3808
3	8	36.9128
3	10	60.3384
3	12	78.7893
3	13	88.7183
3	***14***	***97.3537***
3	30	97.3537
4	16	83.7993
4	18	93.7688
4	***19***	***99.9061***
4	20	99.9061
5	20	84.4271
5	22	94.817
5	23	99.3394
5	24	99.3394
5	***25***	***100***

Take the highest successful probability and the optimized time, we get the statistic histogram below in Figure 4-6 and Figure 4-7:

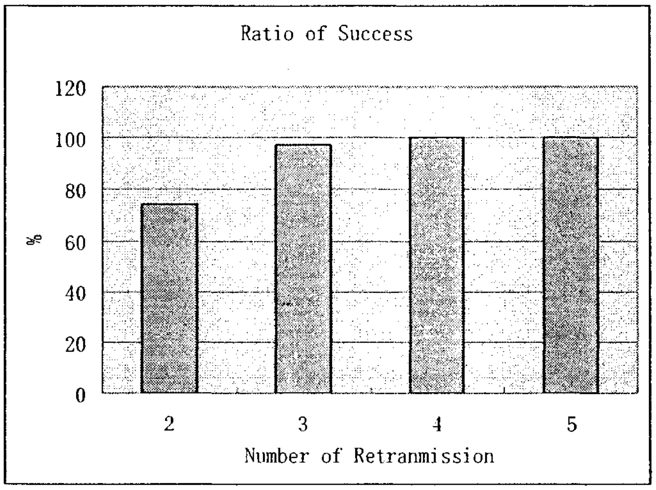


Figure 4-6 Number of Re-transmissions VS Ratio of Success

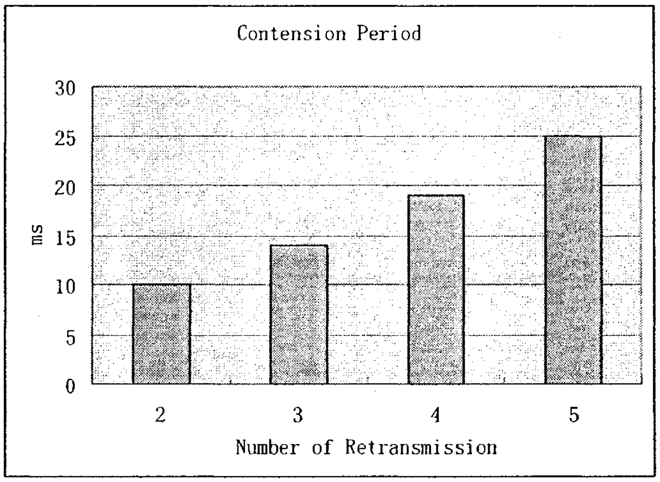


Figure 4-7 Number of Re-transmissions VS Contention Period

2) Comparison and Analysis of Theoretical Value and Simulation Results

Chapter 3 gives the theoretical deriving expression of Ps, which shows that it is influenced by the length of contention window CW, the number of backoff times and the number of nodes in the network. As the expressions are so complicated that it is difficult to solve the relations between Ps and other variables, in order to figure out how these variables impact the value of Ps, we used approximation method and get successful reserving probability under different number of n and W. The following Table 4-2 gives various results of Ps:

Table 4-2 Ps Value under Different Conditions

Nodes Number Re-Transmission Times	N=5	N=10	N=20
2	t=0.0292980 Ps=0.941430	t=0.0273023 Ps=0.880072	t=0.0246969 Ps=0.780406
3	t=0.0291889 Ps=0.941648	t=0.0267517 Ps=0.882450	t=0.0231638 Ps=0.793137
4	t=0.0291630 Ps=0.941700	t=0.0265152 Ps=0.883463	t=0.0222827 Ps=0.800509

According to the data in the table above, random contention access rate will be higher along with the increasing re-transmission times, this is because failed nodes in the contention will win more chance to access the channel; meanwhile, the increases of nodes number in the network will lower the value of Ps, this is because when there are more competitors in the channel, under the same data capacity of each node, this change is equal to a more crowd channel.

Comparing and analysis with the simulation data above, data obtained by system simulator has some differences from theoretical value due to the accuracy extent of our theoretical model. However, changing trend and relationship reflect among Ps, nodes number and re-transmission times are the same. The figure below is the comparison of theoretical derivation and simulation when we take n=5 for instance.

Comparison diagram of theoretical value and simulation results is shown below in Figure 4-8:

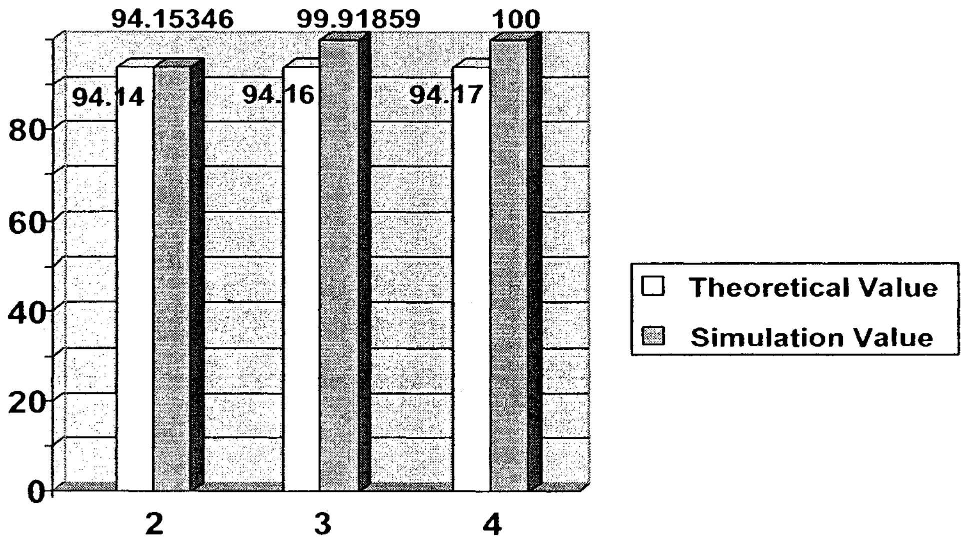


Figure 4-8 Theoretical Value vs. Simulation Value

3) Simulation Analysis

According to the simulation results above, we get that when re-transmission times is constant, prolonging contention period can increase the probability of contention successful rate, however, when increasing to some extend, the probability will get to a maximum value and will not change any more. Besides, if we add re-transmission threshold and give sufficient time for contention period, the maximum successful contention probability will theoretically increase, too. For example, if we set re-transmission threshold as 5, the maximum successful contention probability can arrive to 100%, but it need longer contention time; if the threshold is set as 3 or 4, the probability can also be obtained as high as 95% while the contention time is decreased greatly. Thus it saves a big amount of energy for wireless sensors which optimized the most significant problem in WSN-Energy consumption.

4.2.2.2 IEEE 802.15.4

1) Simulation Results

According to IEEE802.15.4 standard, re-transmission time is set as 3. Consider the proportion of CAP and CFP; we allocate 10 slots for CAP and 5 slots for CFP. Meanwhile, since IEEE 802.15.4 contains inactive phase, to make sure the two protocols are comparable, in the simulation of NS-2 later on, we set the superframe in IEEE 802.15.4 (CAP+CFP+INACTIVE) the same length as CRMAC. That is, to compare the two protocols under the same conditions. More details are seen in 4.3.

In CAP phase, we still use OPNET to do the simulation; simulation modeling is set the same as CRMAC and only modified the value of data source and set the attribute of Time Interval as 10 slots, that is,

$$50\text{ms} = 10\text{slots}*5\text{ms}$$

Through simulation, after CAP, we obtained Figure 4-9 based on the numbers of data packets that central nodes received. The smooth curve is obtained from three layer curve-fitting of the simulation results.

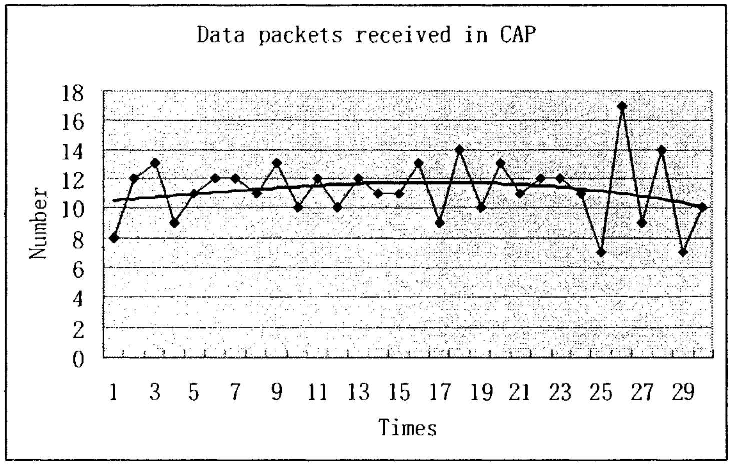


Figure 4-9 Data Packets Received in CAP

2) Simulation Analysis

In this simulation, set fixed re-transmission threshold and contention period. 3/4 of nodes in the network will transmit data using contention mechanism, while the other 1/4 of nodes only perform CFP slot reservation during contention period. Due to too many nodes transmitting data in CAP that some of the nodes will fail in the contention so central nodes will receive different number of packets in each round of contention phase. Average packets received in each CAP are about 11.2. This number will also be contributed to NS-2 simulation later for IEEE 802.15.4's throughput.

4.2.3 OPNET Simulation Results Abstract Value

4.2.3.1 CRMAC

For the following simulation in NS-2, meanwhile consider the comparison with IEEE 802.15.4 later. Here we choose a re-transmission threshold as 3. Considering longer competition time will lead to excessive energy consumption, which system's life-cycle will decline; as well as guarantee certain competition successful rate, we selected the parameters from the simulation as follows:

1) Re-transmission times: 3
2) Contention period: 10ms
3) Successful contention access probability: 60.3384%

Among them, 10 ms contention period equals to two slots. Energy consumption in this time period will be counted as a part of total system energy consumption statistics in the follow-up NS-2 simulation. Since contention reserve step did not send real data, so at this step no throughput statistical information will produced.

4.2.3.2 IEEE 802.15.4

According to IEEE 802.15.4 standard, we selected the following parameters:

1) Re-transmission times: 3
2) Contention period: 50ms
3) Central node receives the number of packets each round in CAP: 11.2
4) Single packet size: 625 byte.

Among them, 50 ms contention period equals to ten slots. Energy consumption in this time period will be counted as a part of total system energy consumption statistics in the follow-up NS-2 simulation. For IEEE 802.15.4, throughput in CAP will produce the statistical information, so 11.2 packets will be counted in NS-2 later.

4.3 Modeling in Guaranteed Data Transmission Step

As mentioned above, in this part we will use NS-2 to complete the modeling and simulation analysis.

4.3.1 CRMAC

1) Central Nodes

From the simulation results that we obtained from OPNET, we select successful contention access probability as 60%. Central nodes needed to do a complete schedule arrangement and broadcast the results. Each round after the central node receives data, it needs to re-schedule and repeat the process above. Flow diagram is shown below in Figure 4-10:

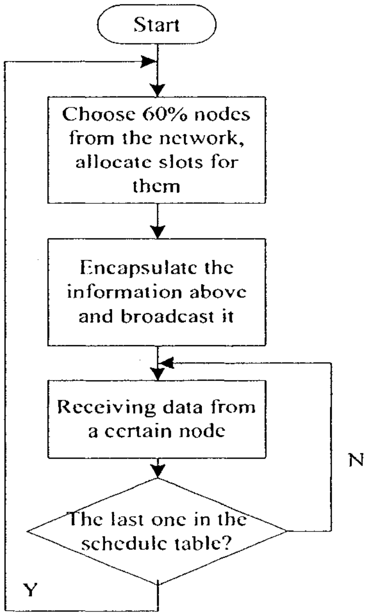


Figure 4-10 Process of Center Node Modeling in CRMAC

2) Common nodes

Modeling for common nodes is simple, which only need to transmit data in the slot according to the schedule table.

3) Specific modeling

[1] Broadcasting Beacon

To make sure that broadcasting bacon is received correctly, allocate one slot for it.

[2] Data application

Since a successfully reserving node may have different sizes of data to transmit, in our simulation, we assume one packet's length is at least 625 bytes (occupy 1 slot) and 3 times of 625 bytes (3 slots) of at most. That is,

$$625*3=1875 \text{ bytes}$$

data to send.

Assume there are 25 bytes of overhead in the 625 bytes. When designing CRMAC, we consider the full usage of slots, so when nodes are applying for data transmission, it can reserve for either integer or non-integer times of slots. Assume that all nodes (20 nodes) have data to send, and they all compete for the channel, based on the simulation results above, we will have about 12 nodes (60%) each round that can transmit data in the following contention free data transmission step.

[3] Length of superframe

Since slots occupied by each node are randomly and uniformly distributed from 1 to 3, the expectation value is then 2 slots. 12 nodes are independent when applying for the slots an the sum obeys normal distribution, which the expectation value is thus,

$$E(sum) = \sum_i E(node_i) = 12 \times 2 = 24$$

So in CRMAC, the length of a superframe is about:

$$\begin{aligned} L &= Contension\_time + Broadcasting\_time + Noncontension\_time \\ &= 2 + 1 + 24 = 27 Slots \end{aligned}$$

Based on the simulation results in OPNET above, as long as mathematical computing analysis and algorithm description before, we can model CRMAC in NS-2. When dealing with data statistic, we need to consider the energy consumption in OPNET.

4.3.2 IEEE 802.15.4

1) Modeling Process for Central Nodes

About 2 (10%) nodes will be reserved successfully in each round. According to IEEE 802.15.4 standard, most of the nodes transmit data in CAP. After each round's data transmission; there will be an inactive period. After this, the central node will re-schedule and repeat the process above. This process is illustrated in the flow diagram below of Figure 4-11:

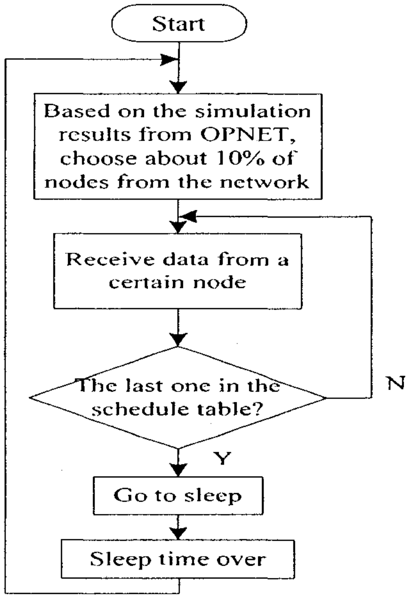


Figure 4-11 Process of Center Node Modeling in IEEE 802.15.4

2) Common nodes

Modeling for common nodes is simple, which only need to transmit data in the slot according to the schedule table.

3) Specific modeling

[1] Data application

Same as CRMAC, each node who have successfully applied for data transmission in CFP may have multiply sizes of packets to send. We also assume 625 byte at least, and 3 of 625 byte at most, that is,

$$625*3=1875 \text{ byte}$$

data to send.

A significant difference between IEEE 802.15.4 and CRMAC is that, nodes can only apply for integer times of basic packet size in IEEE 802.15.4.

[2] Length of inactive period

Since slots occupied by each node are randomly and uniformly distributed from 1 to 3 integer value, the expectation of each node is 2 slots. Then 2 nodes are independent when applying for slots and the sum obeys normal distribution, which the expectation value is thus,

$$E(sum) = \sum_i E(node_i) = 2 \times 2 = 4$$

That is about 4 slots for CFP.

To make sure IEEE 802.15.4 and CRMAC are compared under the same condition, set the superframe of two protocols as the same length, so sleeping (inactive) period in IEEE 802.15.4 is:

$$\begin{aligned} \text{Sleep\_time} &= \text{Superframe} - \text{Contention\_time} - \text{Noncontention\_time} \\ &= 27 - 10 - 4 = 13 \text{ Slots} \end{aligned}$$

That is, there are 13 slots of inactive period in IEEE 802.15.4.

According to the simulation results in OPNET, as well as mathematical analysis and algorithm description, we can model IEEE 802.15.4 in NS-2. When dealing with data statistic, we need to consider the information of energy consumption and throughput from OPNET.

4.3.3 Comparison of Superframe Structure

According to the analysis in 4.3.1 and 4.3.2 above about the superframes between two protocols, we get the comparison diagram of superframe structure in Figure 4-12:

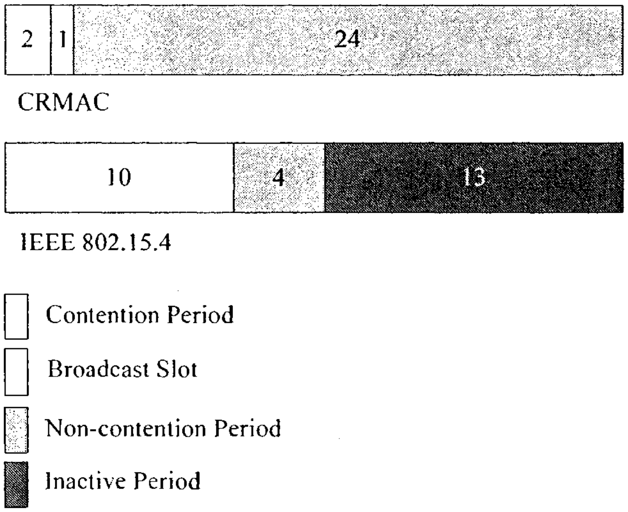


Figure 4-12 Comparisons of Superframe Structures

4.4 Final Simulation Results

4.4.1 Energy Consumption

Assume central nodes have continuous energy supply, so we only need to calculate and compare common nodes' energy consumption. One common node's energy consumption in a WSN by using IEEE 802.15.4 and CRMAC are compared below in Figure 4-13. The consecutive curve is energy statistic curve of CRMAC; we can see that, comparing to IEEE 802.15.4, when using CRMAC protocol, energy consumption is lower accordingly.

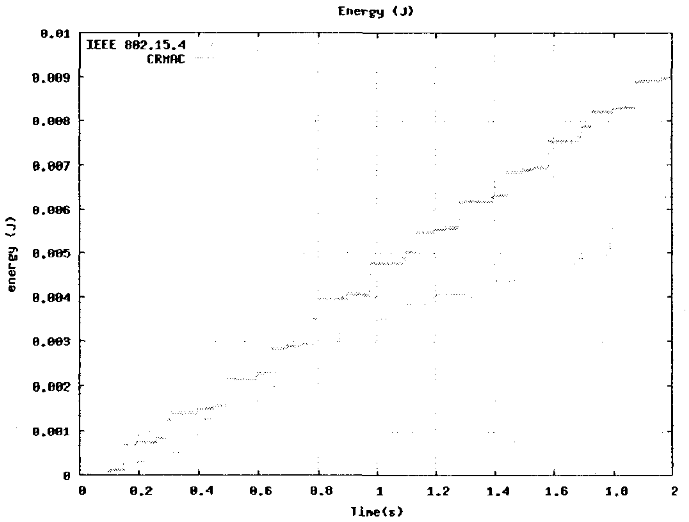


Figure 4-13 Energy Consumption Comparisons

In Figure 4-13, two curves have an overall upward trend, which is because energy consumption is gradually increased along with the growth of time; strong vibration of two curves is because of the following reasons:

1) For IEEE 802.15.4, nodes spend most of the time of the superframe in contention phase, we have:

$$\frac{contention\_time}{E(noncontention\_time\_node)} = \frac{10}{2} = 5$$

Which means the proportional value of contention reserve phase and schedule phase is 5, and

$$E(noncontention\_time\_node)$$

means the average expectation value for nodes who successfully compete the channel for none contention step; while for CRMAC, the time that a node spends in contention step in the superframe is much shorter than in IEEE 802.15.4. we have:

$$\frac{contention\_time + broadcasting\_time}{E(noncontention\_time\_node)} = \frac{2+1}{2} = 1.5$$

which means the proportional value of contention phase and schedule phase is 1.5, and

$$E(noncontention\_time\_node)$$

means the average expectation value for nodes who successfully compete the channel in none contention step.

In a word, nodes spend the time in contention phase is much shorter in CRMAC, which means in IEEE 802.15.4, nodes need to stay active for longer time, Thus the energy consumption curve of IEEE 802.15.4 is overall above CRMAC.

2) In these two curves, when slope is larger, nodes are in data transition state (active state). While with smaller slope, nodes are in sleep (inactive) state or do not in the working slot of schedule table, nodes only consume 1mW of power in inactive state, so it is much smaller compare to active state.

3) Curve fluctuation is not quite the same in each superframe; this is because nodes are either success or failure in contention reserve step. For successful nodes, slots they reserved are not the same in each round. Thus curve has some randomization in short term. By Figure 4-14 we get the long term statistic of nodes' energy consumption shown as some stability to some extend.

Figure 4-14 shows the simulation results which we also add the comparison with LEACH Protocol as a complimentary, although MAC protocol in LEACH is not the same as in CRMAC which using hybrid mechanism, as a classic TDMA mechanism earlier and also a very important reference of designing CRMAC, we also give out its energy simulation curves. The figure below shows the simulation for a 600s of time period. Each node's original energy is 2J, when a node consumes 2J of energy, it will lose its effect and stop calculating its energy information. In these three protocols, LEACH first consumes up its 2J energy because it first ran the clustering set-up task, the energy burst during 100s to 120s of time period is when the node is taking the responsibility as a cluster-head. From the figure we can see, the curve is more perpendicular in IEEE 802.15.4, the slope is larger than CRMAC which lead to arrive 2J energy value sooner. When system uses CRMAC, the overall efficiency of life-time according to the simulation is longer than in IEEE 802.15.4. Curve vibration is due to each time slots allocation is different. Although in IEEE 802.15.4 we also add sleeping period which can prolong the system life-time, due to its relative longer contention period, it still consumes more energy compared to CRMAC, by simulation we get integrated efficiency of system lifetime is still shorter in IEEE 802.15.4.

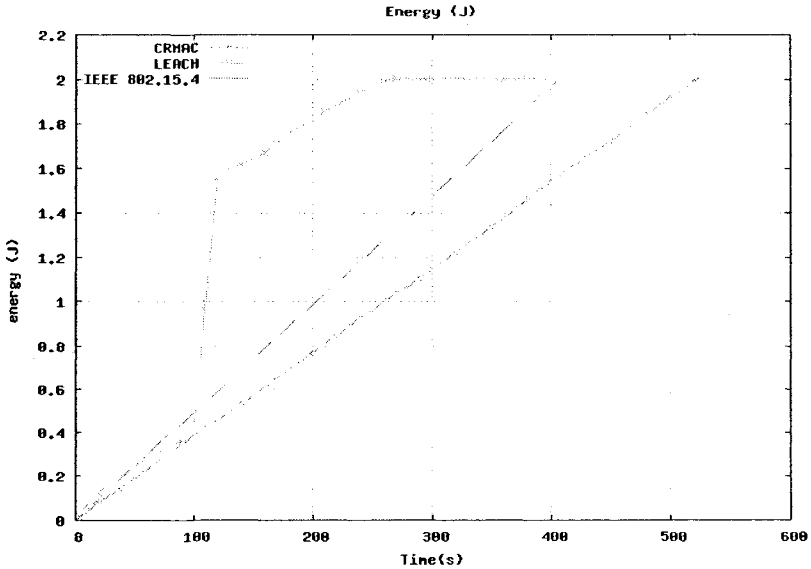


Figure 4-14 Comparison of Lifetime

4.4.2 System Delay

Delay situation of cluster-head that receives data from each node is drawn below in Figure 4-15. Because in IEEE 802.15.4, nodes successfully reserve the slots need to wait for transmission until next superframe. Accordingly, its delay will be larger. Compare the simulation results in statistic average; average delay in IEEE 802.15.4 is 150.56ms; while using CRMAC is 68.61ms. So delay is better in CRMAC. Since data transmission task is periodic, so delay is also changed periodically in the figure. LEACH Protocol uses cluster-head election mechanism, whose delay character has no comparison with the other two protocols including CRMAC hence we do not hand out the delay comparison with LEACH in this simulation.

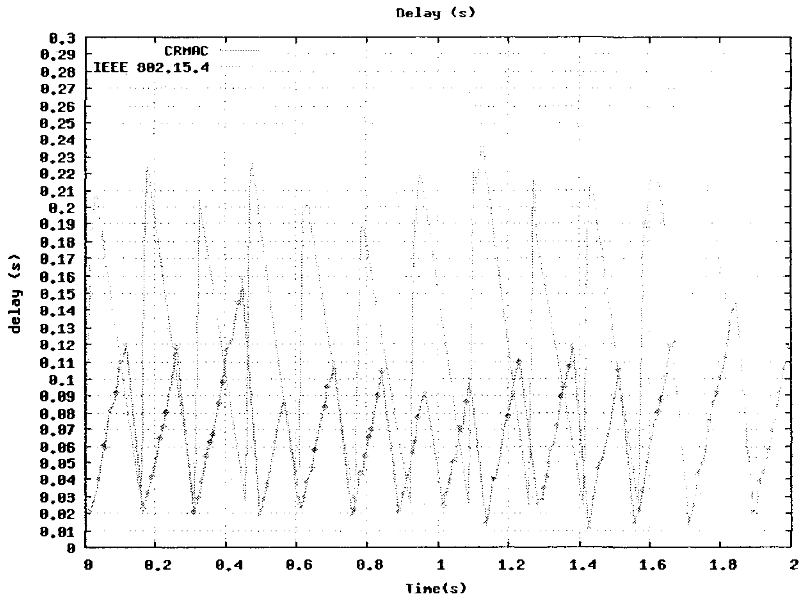


Figure 4-15 Comparison of Delay

4.4.3 Throughput

Figure 4-16 shows throughput comparisons among three protocols. In IEEE 802.15.4, due to higher possibility of collision that may happen in transmitting data in contention period, it may lead to a drop of data after times of retry. Meanwhile, long duration of sleeping period may be lower the service rate and therefore, will lead to lower throughput: about 150kbit/s in the simulation. On the other hand, CRMAC protocol allocates the channel by slots, there won't be collision. Besides it does not have a sleeping period in this step, the protocol will process a better throughput and higher service rate: about 725kbits/s. Based on the data from the simulation, throughput in CRMAC is about 4.83 times of IEEE 802.15.4. Comparing to the two protocols above, the throughput curve in LEACH protocol has more twists and turns, that is because there are more interactive information when the nodes are act as cluster-head, which leads to bigger fluctuate in throughput. Around 300s, throughput declines sharply due to many nodes die out.

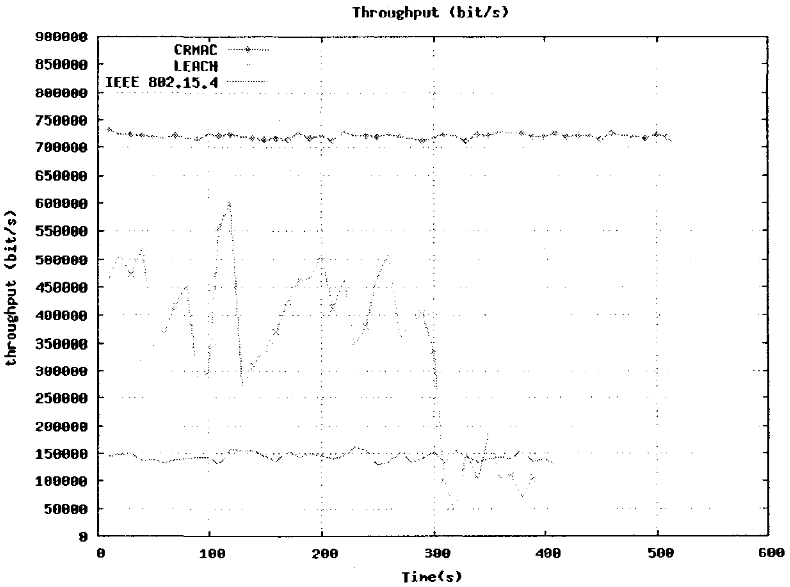


Figure 4-16 Comparison of Throughput

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

Along with the rapid development, WSN has a very wide application perspective. It is now one of the research focuses and hot points in the perspectives of information receiving and area monitoring. This paper first gave a description of WSN and pointed out that design of MAC layer has a vast influence on the performance of WSN. It then analyzed the design requirements of WSN MAC protocols as well as main elements lead to energy consumption in MAC layer; we conclude that reducing idle listening and data re-transmission are the most efficient methods to decrease energy consumption. The paper also compared the characteristics between contention-based and schedule-based MAC protocols, as well as the pros and cons of applying them into WSN technology. We specialized some familiar MAC algorithms, analyzed their working mechanisms as well as their advantages and disadvantages, accordingly. Based on these, we proposed high energy efficiency, contention reserve algorithm on the basis of clustering idea, and this algorithm formulates the advantages of both contention-based and schedule-based algorithm, by using the way of random backoff to compete for the channel and transmit node's short communication reserve packets. While important data transmissions will use schedule mechanism, which can increase the energy efficiency by a high step, meanwhile ensuring network throughput and extending the network life-cycle. Besides, we modeled our protocol and analysis its energy consumption; through network simulations, we testify the advantage of our protocol in terms of network delays, throughput, and energy consumption.

To judge which protocol is the better than the other ones is not reasonable in WSN, since none of the protocols have more specific or obvious advantages than the others in terms of performance and energy saving effect. Each self-adapt modifications and optimizations are all increasing some specific parameters while sacrificing some other properties as trade-offs. WSN is an application-oriented network, before designing a network protocol or evaluating an algorithm, it should first clarify the network's task, which is to find the best balance point of sacrifice the costs and prospect performance. According to specific application scenarios in WSN, thoroughly consider and select the most optimal MAC protocol to get the best network performance. For relative stability of the state, large data, long life-circle requirements of commercial and industrial monitoring sensor networks, the use of CRMAC protocol will get relative advantages in energy consumption, network throughput and delays. However, although CRMAC mixes the advantages of contention and non-contention algorithms and achieves better network performance results, there are still many improvements to make such as:

1. CRMAC is based on clustered network structure, and hence is restricted by clustering algorithm and network structures. While in large-scale WSN

applications, distributed network architecture has superior flexibility and scalability. Flat network structure can also reduce network deployment time in some extent, and reduce the complexity of network management. Therefore, to improve CRMAC algorithm and make it adapt to the distributed network structure is a very important research direction in the future.

2. Although by using schedule-based mechanism, CRMAC generates good results in terms of avoiding the conflicts, it also reduces the flexibility of network expansion which is performed in not sensitive to the departure of the old nodes (due to damage or move) or the arrival of the new nodes in the network. It needs to go through complicated information interaction and quite a period of time to coordinate and implement. For a standard WSN, it is inevitable for node changes in the network topology, therefore CRMAC protocol needs to be further improved in its network topology adjustments.
3. In contention free data transmission step, timing problem is also of concern. In IEEE 802.15.4 superframe structure, the protocol provisions the whole process to comply with timing. CRMAC's definition is a bit more complex which engineering application software will cost more, if applied it to the actual realization of the project, it should use optimized software in order to improve its efficiency.

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