國 立 交 通 大 學

電 信 工 程 學 系

碩 士 論 文

適應信標間距的智慧型路由器之無線隨意網路
媒體存取控制協定

Intelligent Router-Assisted Power Saving Medium
Access Control for Mobile Ad Hoc Networks with
Adaptable Beacon Intervals

研究生 ：周冠宏

指導教授 ：方凱田

中 華 民 國 95 年 6 月

適應信標間距的智慧型路由器之無線隨意網路媒體存取控制協定

Intelligent Router-Assisted Power Saving Medium Access Control for
Mobile Ad Hoc Networks with Adaptable Beacon Intervals

研究生 : 周冠宏　　　　　　　　　Student : Kuan-Hong Chou

指導教授 : 方凱田　　　　　　　　Advisor : Kai-Ten Feng

國 立 交 通 大 學

電信工程學系碩士班

碩士論文

A Thesis
Submitted to Department of Communication Engineering
College of Electrical and Computer Engineering
National Chiao Tung University
in Partial Fulfillment of the Requirements
for the Degree of
Master of Science
in Communication Engineering
June 2006
Hsinchu, Taiwan, Republic of China

中 華 民 國 95 年 6 月

適應信標間距的智慧型路由器之無線隨意網路媒體存取控制協定

學生 : 周冠宏　　　　　　　　　　　指導教授 : 方凱田

國立交通大學電信工程學系碩士班

摘　　要

在無線隨意網路中，電池量是有限的，所以節省電池量一直是個重要的研究議題。在一些舊有的媒體存取控制的協定裡，雖然達到了省功率的效能，但是也浪費了頻寬，包括封包的延遲時間，傳送率等等。那我們提出的智慧型路由器演算法，就是能預測封包經過的下一個節點，在媒體存取控制層，我們利用一塊記憶體去紀錄擇路層的資訊，使我們在媒體存取控制曾就可以把封包快速的送到目的地。並且我們也發現信標間距的大小也會影響功率的消耗，IEEE 802.11 的省電機制，信標間距是固定的，會造成頻寬的浪費，所以我們計算適應性信標間距，計算出我們要的信標間距，不會造成頻寬的浪費，也節省功率的消耗。在配合我們的智慧型路由器演算法，達到省功率，減少延遲時間，節省頻寬等好處。

Intelligent Router-Assisted Power Saving Medium Access Control for Mobile Ad Hoc Networks with Adaptable Beacon Intervals

Student : Kuan-Hong Chou   Advisor : Kai-Ten Feng

Department of Communication Engineering
National Chiao Tung University

Abstract

The limitation on the battery life has been a critical issue for the advancement of the mobile computers. Users encounter unsatisfactory battery power while using their mobile devices, especially on the occasions of transmitting data using the wireless networks. It has been studied that the amount of energy consumed within the mobile devices is significantly affected by the design of the Medium Access Control (MAC) protocol within the wireless interface. This thesis presents a Intelligent Router-Assisted (IRouter) power-saving MAC algorithm that achieves energy conservation by predicting the next hopping node within the delivering route. With the assistance of the intelligent routers in the network, the packet delivery between several mobile nodes can be accomplished within the same beacon interval. It has been studied that the duration of the beacon interval is relative to the power consumption. In this thesis, we adjust the duration of the beacon interval in the IRouter scheme to conserve energy, and the concept of adaptable beacon interval is presented. The performance comparison between the proposed IRouter algorithm and the existing MAC protocols is conducted via simulations. It is observed that the IRouter scheme can achieve feasible performance in both energy conservation and routing efficiency.

誌　謝

　　千呼萬喚始出來，兩年多來所做的東西，都收錄在這本論文裡面。首先要感謝的就是我的指導教授方凱田教授，老師提供了很多想法及方向，讓我在茫茫的學海中，找到了燈塔並指引方向。再來就要感謝電信的李程輝教授跟資工的趙禧綠教授，撥空來參加口試，並給了許多寶貴的意見，並順利讓我通過口試。

　　接著要感謝的就是實驗室的戰友(死歐、雄光、中義、小華、阿魯咪)，因為大家都同在屋簷下，所以更要一起努力。還要感謝這兩年來認識的許多人(小瑩、小南、恆如、寶寶、小巫、小魚、小紫)，在我研究所苦悶的時候，豐富了我的生活。當然還有實驗室學長跟學弟們，也給予我一些幫助。最後要感謝的就是我的家人，家是最溫暖的避風港，不管什麼時候家人都會給我溫暖的祝福，還會到廟裡替我拜拜，保佑我一切順利，所以也要感謝暗中保佑我的神明。最後的最後，也要感謝一下自己，這兩年來有苦有樂，苦的時候自己也都撐過去了，實在是太偉大，太厲害了，不由得佩服一下自己。要感謝的人太多了，不是短短幾個字能表達我內心的感謝，所有對我好對我關心的人，我都非常感謝，謝謝大家，我終於不負大家期望畢業了。

<div style="text-align: right">

周冠宏謹誌　于交通大學

2006　6 月

</div>

Contents

List of Figures

4

Chapter 1

Introduction

A Mobile Ad hoc NETwork (MANET) consists of wireless Mobile Nodes (MNs) that cooperatively communicate with each other without the existence of fixed network infrastructure. Fig. 1.1 shows the framework of wireless ad hoc network, where each MN communicates with others not via infrastructure but the peers. Depending on different geographical topologies, the MNs are dynamically located and continuously changing their locations. Recent interests in the design of MANET algorithms include applications for the military, the Inter-Vehicle Communication (IVC), the Personal Communication Services (PCS), and the sensor networks. The MANET is not only used in military communication but can also be applied generally in Inter-Vehicle Communication (IVC), message delivery, disasters recovery, sensor network, the Personal Communication Services (PCSs), and educational purpose. There are two examples of MANET described as follows:

- **The Intelligent Transportation System (ITS):** With the capability of self-organizing, the MANET provides the wireless communication routes between vehicles. This capability is also useful when emergencies happen in rural area because it will be much easier to communicate with police using MANET. Similarly, the MANET can help to save lives in mountains or in seas which have no expected network infrastructure provided. In the limited space and time, the MANET is especially satisfactory because of its wireless and movable features.
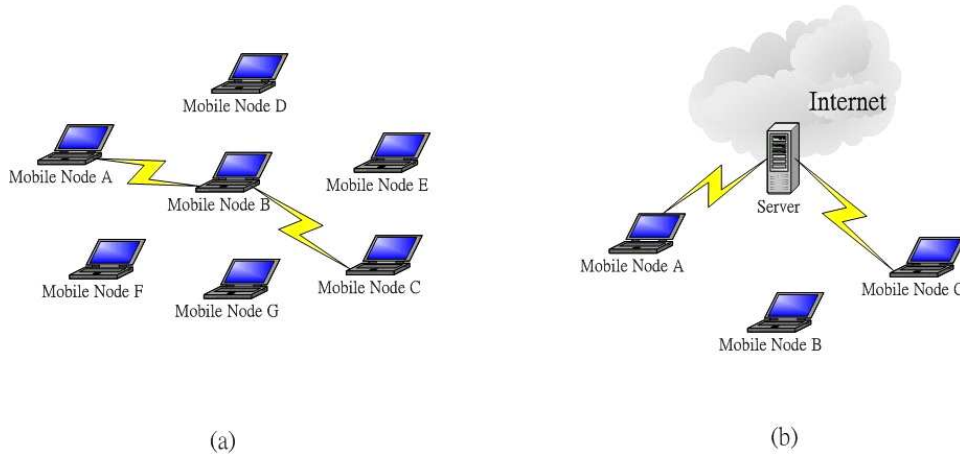
Figure 1.1: (a)Ad hoc Network: Node A Communicate with Node C via Mobile Node (b)Infrastructure Network: Node A Communicate with Node C via Infrastructure

- **The Personal Communication Service (PCS):** As the personal communication devices are becoming more powerful, the related technology is required to deal with mass data transmission, including computer files exchange and exhibition of application programs. The MANET can provide data transmission efficiently by forming a temporary network topology instead of a large infrastructure or a point-to-point transmission line.

Since most of the MN's are battery-powered devices, how to minimize the MN's energy consumption becomes an important issue in the protocol design within MANETs. In the infrastructure-based networks, the MNs can be scheduled to be in the sleep state by the centralized server while they are not actively transmitting or receiving data. However, it is challenging to design a feasible power control mechanism within the decentralized and fast-changing ad hoc networks [1]. An efficient power-saving mechanism should be incorporated within the protocol design in order to conserve the MN's energy; while the routing efficiency can still be preserved under the dynamic changing networks.

Many research studies have been carried out in the design of power-saving mechanism for MANETs. The protocol designs are considered in different network layers [2]- [12], especially in the Medium Access Control (MAC) layer and the routing layer. A feasible design of the power-saving MAC scheme will be the primary focus in this thesis.

7

However, most of the research studies consider their power-saving MAC schemes within a single hop between the MNs. The power level of the MN is turned to the sleep state while it is not either transmitting or receiving data packets. A large amount of the existing power-saving schemes conserve the MNs' energy but induce worse routing efficiency, including longer end-to-end routing delay and excessive packet loss. In this thesis, an Intelligent Router-Assisted (IRouter) power-saving MAC protocol is proposed to offer efficient packet delivery with minimal power consumption for the MANET. The proposed IRouter scheme incorporates partial routing information within the power-saving MAC protocol design. Each MN maintains a cache memory which updates the information of the predicted next hopping nodes within the delivering routes. Based on the partial routing information, multi-hop packet delivery can be achieved within a single beacon interval. The proposed IRouter scheme results in improved routing efficiency and power consumption within the MAC layer. The effectiveness of the IRouter MAC algorithm is validated via the simulation results.

Some of the research show that the duration of the beacon interval affects the power consumption. In the IEEE 802.11 PSM, the beacon interval is divided into the ATIM window and the remaining beacon interval. The duration of the ATIM window and the remaining beacon interval will also affect the power consumption. If the duration of the beacon interval is large, the power consumption will increase; while the duration of beacon interval is short, the numbers of control packets will increase. There is tradeoff between the power consumption and the numbers of control packets. We will calculate the duration of adaptable beacon interval (ABI), which allows one transmission pair. According to our presented cost function, we can determine the transmission pairs that are allowed in one beacon interval. The adaptive beacon interval scheme will be added to the IRouter algorithm to further provide efficient energy conservation.

The remainder of this thesis is organized as follows. Chapter 2 introduces the key components and related work of MANET in MAC layer. Chapter 3 shows the analysis of adaptable beacon intervals (ABIs). The proposed IRouter algorithm is presented in Chapter 4. The simulation parameters and the performance evaluation of the proposed IRouter algorithm are

shown Chapter 5.1 and 5.2. Chpater 6 draws the conclusions.

Chapter 2

Key Componets and Related Work in MANET

In this section, the key components which enable the communication in ad hoc networks will be presented.

According to the structure of Open System Interconnect (OSI), the radio propagation model are utilized to formulate the radio phenomenon and the baseband system to achieve the data transmission between MNs in the physical layer. In the MAC layer, how nodes share the same medium is an important issue in the wireless system. How to decide the routing path between the source nodes and the destination nodes is considered in network layer. In this thesis, we focus on the MAC protocols, so the MAC layer protocols will be studied in section 2.1. The IEEE 802.11 power-saving mechanism (PSM) will be described in section 2.2. Some MAC power-saving protocols will also be investigated in section 2.3.

2.1 MAC layer

In this section, the mechanisms of IEEE 802.11 Medium Access Control (MAC) are described. The MAC layer provides several services, including packets exchange, synchronization, and channel utilization. It is also responsible for interpreting the received bit stream from the physical layer to the network layer.

2.1.1 Distributed Coordination Function

The Distributed Coordination Function (DCF) is a basic access mechanism utilized by the MAC protocol in IEEE 802.11. The DCF is based on a Carrier Sense Multiple Access (CSMA) with Collision Avoidance (CA), which guarantees each station a fair chance to access the medium.

By using the CSMA/CA scheme, each node has to sense the medium before data transmission. If the medium is found idle, the data is allowed to be sent. In order to avoid collision, the station selects a random backoff time slots and freezes transmission until the time slot is decreased to zero. The MANET is a self-organized network without centralized node to control the usage of medium. The IEEE 802.11 DCF is a simple and fair mechanism that satisfies the requirement of MANET.

However, the fast changing characteristic of wireless medium makes the correct operation of carrier sense a difficult problem. The IEEE 802.11 MAC protocol provides additional mean called virtue carrier sensing as a backup mechanism to avoid collisions. Virtual carrier sensing is carried out by NAV (Network Allocation Vector), which records the duration of ongoing data transmission. The data can be transmitted only when both physical and virtual carrier sense mechanism detect that the medium is idle.

Before the data transmission, each station executes backoff process to ensure the low probability of collision. The station uniformly selects the time slots between the interval of $[0, CW]$, which is predefine by IEEE 802.11. The minimum of contention window (CW) size is 31. The maximum of contention window (CW) size is set to be 1023. However, the stations may choose the same time slots under congestion networks. The binary exponential backoff algorithm is executed by using double CW size to avoid the collision again.

The IEEE 802.11 MAC defines multiple Inter Frame Space (IFS) which are utilized to provide different priorities for medium access including short IFS (SIFS), PCF IFS (PIFS), DCF IFS (DIFS), and Extended IFS (EIFS). As shown in Fig. 2.1, the SIFS is the shortest time spacing with which the station can immediately response the request like Ack and CTS. The Point Coordinator Function (PCF) is a contention free service and the infrastructure

11
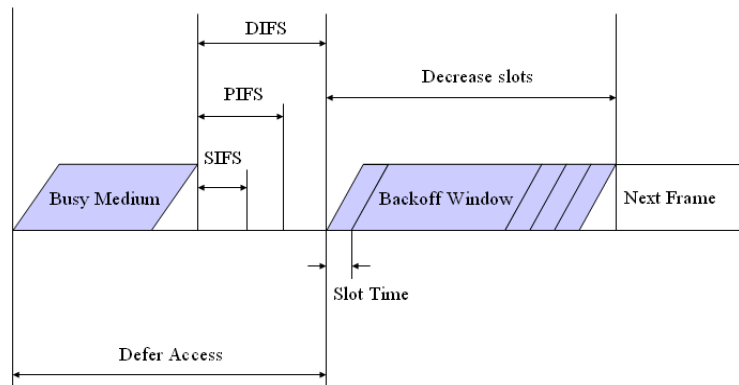
Figure 2.1: The Medium Access via Different Inter Frame Space (IFS)

is responsible for monitoring the transmission between each station. To ensure the service being contention free, DIFS > PIFS can avoid the DCF interfering the transmission of PCF. Finally, waiting the largest time spacing EIFS means the packet retransmission (i.e. collision occurs).

2.1.2 Hidden Node Problem

Due to the limited transmission range, the CSMA can not detect the data transmission that are out of the sensing range, which causes the hidden node problem. The hidden node problem will result in the degradation of performance. As shown in Fig. 2.2, the node A is transmitting a packet to node B. At this moment, the node C also initiates a new transmission but the carrier sense can not function since C is outside the transmission range of node A. The collision will occur at node B and node A has to retransmit the packet.

The solution of hidden node problem is that each station exchanges smaller packets called RTS and CTS to reserve the channel before data transmission. In Fig. 2.3, node A sends RTS to node B and node B replies a CTS to node A. It is noted that node C is also informed not to send packet by receiving the CTS.
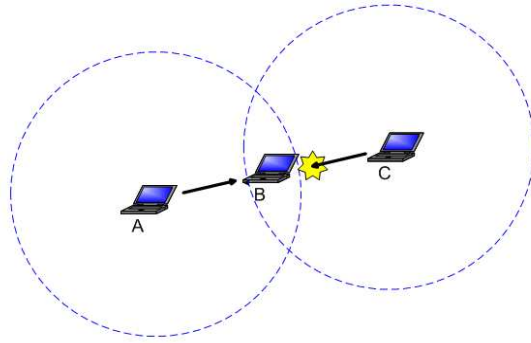
Figure 2.2: Hidden Node Problem
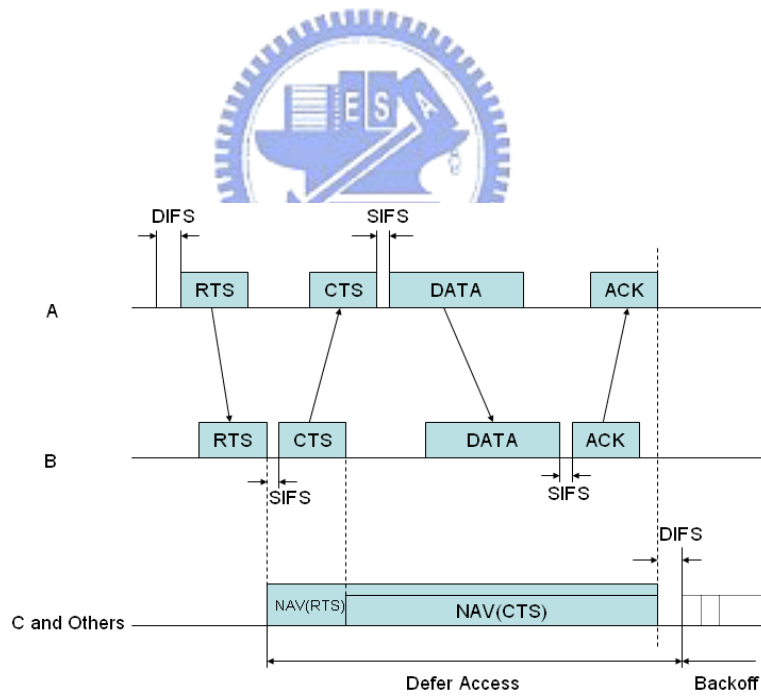
Figure 2.3: Timing Diagram of RTS/CTS Packet Exchange
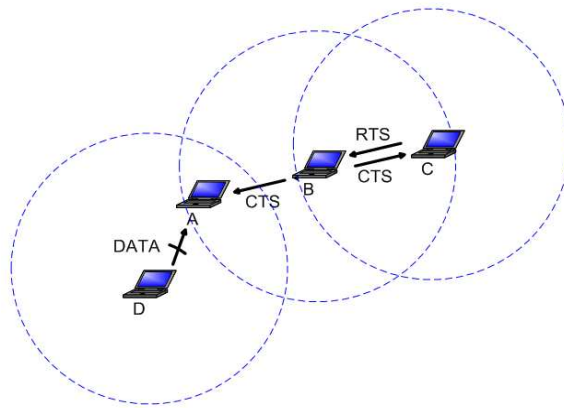
Figure 2.4: Exposed Terminal Problem

2.1.3 Exposed Terminal Problem

The RTS/CTS mechanism protects the data by blocking the nodes around the transmission pair, which degrade the throughput of network. Fig. 2.4 shows the exposed terminal problem. Because node A is blocked by the CTS of node B, node D can not send its packet to node A even if this transmission will not affect node B and node C.

2.2 IEEE 802.11 Power-Saving Mechanism (PSM)

In ad hoc networks, battery power is an important resource since most terminals are battery powered. Terminals consume extra energy when their network interfaces are in the idle state or when they overhear packets not destined for them. They should, therefore, switch off their radio when they do not have to send or receive packets. IEEE 802.11 features a power saving mechanism (PSM) in Distributed Coordination Function (DCF). In PSM for DCF, nodes must stay awake for a fixed time, called the ATIM window (Ad-Hoc Traffic Indication Map window). If nodes do not have data to send or receive, they enter the sleep state except for the ATIM window duration. However, ad hoc networks with PSM have longer end-to-end delays to deliver packets and suffer lower throughput than the standard IEEE 802.11.

The IEEE 802.11 PSM [2] is adopted as the baseline mechanism for the proposed IRouter scheme, and the IRouter scheme will be described in chapter 4. The primary functionality
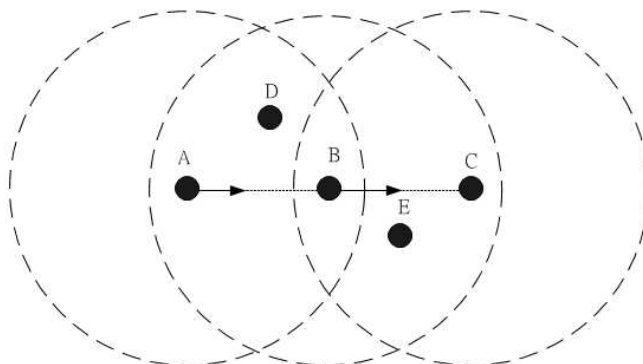
Figure 2.5: An Example of Network Topology

of the PSM is to reduce the power consumption by setting those inactive MNs into the sleep state. As illustrated in Fig. 2.5, the partial route for transmitting data from node A, via B, to C are selected by an ad hoc routing algorithm. It is noted that nodes A and C are not in the directed communication range. The timing histories of the three MNs, A, B, and C (as shown in Fig. 2.6) are divided into Beacon Intervals (BIs). The BIs are synchronized by sending beacon frames between the MNs, which also signal all the MNs to be in the awake state. The PSM defines the ATIM window starting from the beginning of each BI as shown in Fig. 2.6. As node A intends to transmit data to node B, it will send out an ATIM frame to all its neighborhood MNs after channel contention. Since the destination information (i.e. the ID of node B) is recorded within the ATIM frame, only node B will respond with an ATIM-ACK frame to acknowledge the reception of the ATIM frame. After the time for the ATIM window elapses, both nodes A and B are set to be in the awake state; while other MNs within the transmission range (i.e. nodes D, and E as in Fig. 2.5) are set to the sleep state. The data can therefore be transmitted from node A to B using either the RTS/CTS scheme or the conventional CSMA/CA mechanism. It is noted that the RTS/CTS scheme is an optional mechanism, which is primarily designed to resolve for the hidden terminal problem [2]. After the data packet has arrived in node B, the transmission from node B to C will follow the similar process in the next BI (or any other BI afterwards depending on the channel contention) as shown in Fig. 2.6.

15
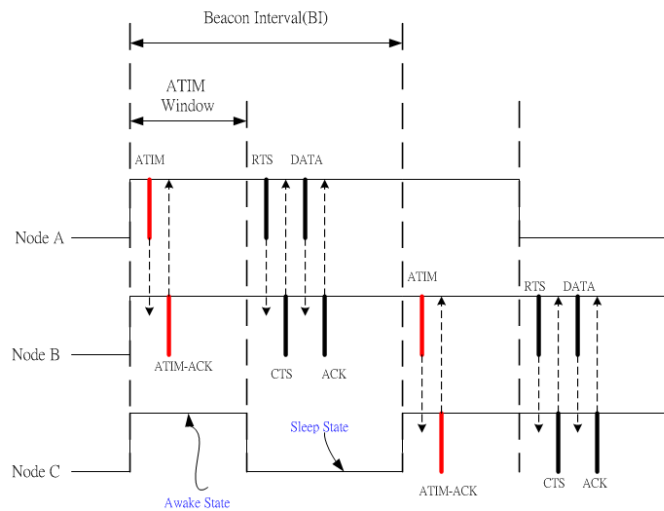
Figure 2.6: The Timing History of Node A, B, and C

2.3 Some MAC Power-Saving Protocols

In this section, some MAC power-saving protocols will be described. It has been observed in [3] that many power-saving schemes are based on the PSM to further improve the energy consumption under different circumstances. The study in [4] shows that the length of the ATIM window within the PSM significantly affects the routing performance. It is noted that the ATIM window is defined as the time interval for determining the MNs to be in the awake state for data transmission. The scheme in [5] modifies the 802.11 PSM by adjusting the length of the ATIM window based on the levels of network congestion. The Power Save Distributed Contention Control (PS-DCC) [6] determines its power-saving strategy by controlling the accesses to the shared transmission channel. The PAMAS protocol [7] utilizes busy tones in a separate signaling channel to control the packet transmission in the data channel. In additions, several routing layer schemes for power-saving purpose are proposed in [8] [9] [10] [11]; while [12] presents a cross-layer power management system for the MANET. Power can be saved during the clustering stage [13] [14], and also by reducing contention in the MAC layer [15] [16]. Also research has been done based on IEEE 802.11s power management scheme, which puts idle stations (those with no traf- fic coming in or out) into sleep by shutting down their transceivers [17] [18] [19]. We will describe three representative MAC protocols; one is

16

asynchronous protocol; another is power controlling protocol; the other is topology controlling protocol.

2.3.1 Asynchronous MAC Protocols

Many MAC protocols are synchronous. In [20] there are three asynchronous power-saving protocols based on the IEEE 802.11 PS mode.

- **Dominating-awake-interval protocol:** The basic idea of this approach is to impose a PS node to stay awake sufficiently long so as to ensure that neighboring nodes can know each other. A PS node should stay awake for at least about half of BI in each beacon interval in dominating-awake-interval protocol. The sequence of beacon intervals is alternatively labeled as odd and even intervals. Odd and even intervals have different structures as defined below (see the illustration in Fig. 2.7). Each odd beacon interval starts with an active window. The active window is led by a beacon window and followed by an MTIM window. The function of MTIM window is like ATIM window. Each even beacon interval also starts with an active window, but the active window is terminated by an MTIM window followed by a beacon window. The above theory guarantees that a PS node is able to receive all its neighbors beacon frames in every two beacon intervals, if there is no collision in receiving the latters beacons. Since the response time for neighbor discovery is pretty short, this protocol is suitable for highly mobile environments. But, the power consumption is very large.

- **Periodically-fully-awake-interval protocol:** two types of beacon intervals are designed in this protocol to reduce the active time: low-power intervals and fully-awake intervals . Low-power intervals and fully-awake intervals have different structures as defined below (see the illustration in Fig. 2.8). Each low-power interval starts with an active window, which contains a beacon window followed by an MTIM window, such that Active Window(AW) = Beacon Window(BW) + MTIM Window(MW). In the rest of the time, the node can go to the sleep mode. Each fully-awake interval also starts with a beacon window followed by an MTIM window. However, the node must remain

17
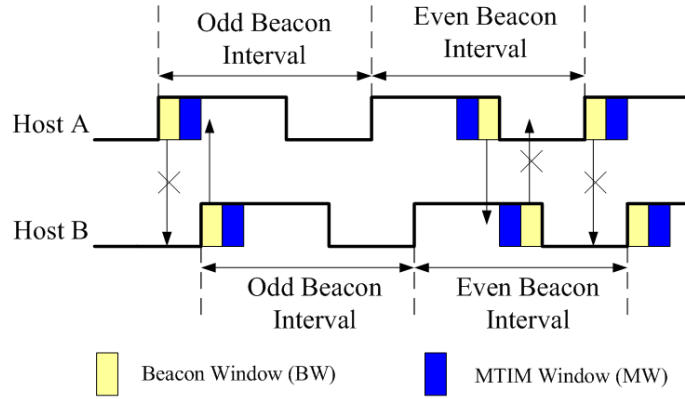
Figure 2.7: Structures of Odd and Even Intervals in the Dominating-Awake-Interval Protocol
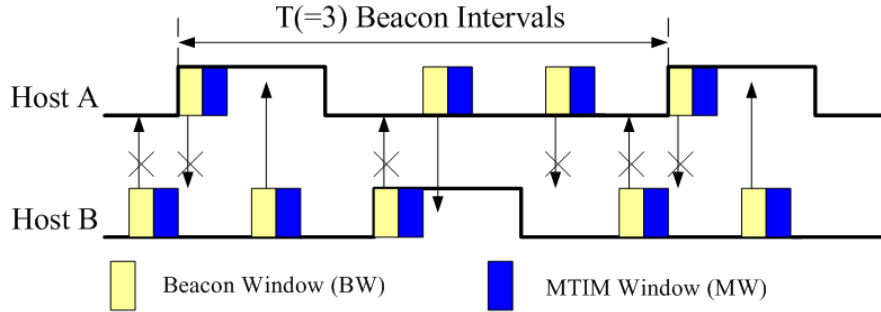
Figure 2.8: An Example of the Periodically-Fully-Awake-Interval Protocol with Fully-Awake Intervals Arrive Every p = 3 Beacon Intervals

awake in the rest of the time, i.e., AW = BI. The beacon intervals are classified as low-power and fully-awake intervals. The fully-awake intervals arrive periodically every p intervals, and the rest of the intervals are low-power intervals. If p is bigger, the power is more efficient.

- **Quorum-based protocol:** In this protocol, a PS node does not need to send beacons in every beacon interval. The sequence of beacon intervals is divided into sets starting from the first interval such that each continuous n^2 beacon intervals are called a group, where n is a global parameter. In each group, the n^2 intervals are arranged as a 2-dimensional $n \times n$ array in a row-major manner. On the $n \times n$ array, a node can arbitrarily pick one column and one row of entries and these $2n - 1$ intervals are called
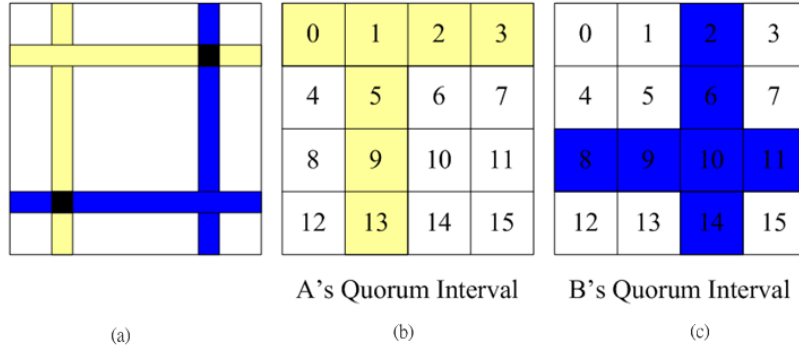
Figure 2.9: Examples of the Quorum-Based Protocol (a)Intersections of Two PS Nodes Quorum Intervals, (b)Node A's Quorum Intervals, and (c)Node B's Quorum Intervals

quorum intervals. The remaining $n^2 - 2n + 1$ intervals are called non-quorum intervals. The structures of quorum and non-quorum intervals are formally defined below. Each quorum interval starts with a beacon window followed by an MTIM window. The node must remain awake for the rest of the interval, i.e., AW = BI. Each non-quorum interval starts with an MTIM window. After that, the node may go to the sleep mode, i.e., we let AW = MW. This is due to the fact that a column and a row in a matrix always have an intersection (see the illustration in Fig. 2.9(a)). Thus, two PS nodes may hear each other on the intersecting intervals. For example, in Fig. 2.9(b) and (c), node A selects intervals on row 0 and column 1 as its quorum intervals from a 4 × 4 matrix, while node B selects intervals on row 2 and column 2 as its quorum intervals. When perfectly synchronized, intervals 2 and 9 are the intersections.

Above three asynchronous MAC protocols are suitable for different environments. Dominating-awake-interval protocol is suitable for highly mobile environment but doesnt conserve energy since it requires PS node to keep active more than half of the BI. Periodically-fully-awake-interval protocol can save more power as long as p > 2 and is more appropriate for slowly mobile environments. Quorum-based protocol only need to send beacons in some BIs. The periodically-fully-awake-interval and the quorum-based protocols active ratios can be quite small as long as p and n, respectively are large enough. The Dominated-Awake-Interval proto-

19

col is most sensitive to neighbor changes, while the Quorum-based protocol is least sensitive.

2.3.2 Power Controlling Protocols

Most MAC protocols are synchronous, and there are usually two broad ways to achieving less energy consumption. One is topology controlling, and another is power controlling. For example, The IEEE 802.11 PSM [2] is topology controlling protocol. The power controlling protocol is changing transmission power with packets.

The algorithm in [21] [22] determines different transmission and sensing ranges to optimize the transmission energy of the MNs.The algorithm belongs power controlling protocol. The node uses maximum power level to transmit RTS and CTS packets as illustrated in Fig. 3.5. Then, the node calculate transmission power, which source node can transmit destination node suitably. Next, the node will transmit data packets with the calculated transmission power level. Because of lower transmitting power, the power consumption will decrease. The power controlling protocol also causes serious hidden node problem. As illustrated in Fig. 2.11, the transmission between node A and B will collide because of the transmission of node C and D. So, many protocols based on the idea of power controlling are developed. The study in [23] shows that the mobile nodes calculate the packet delivery cure, and modify transmission power. It shows that modes use adaptive power based on packet delivery curve. It is shown that CAPC [23] achieves similar throughput and higher throughput/energy consumption ratio than IEEE802.11 MAC protocol.

2.3.3 Topology Controlling Protocols

There are many topology controlling protocols. These protocols are usually based on the IEEE 802.11 PSM [2]. The algorithm in [24] has two functions. One is scheduling, and the other is dynamically adjusting the ATIM window size. The scheduling is proposed to avoid PS nodes contending medium again after the ATIM window without any extra overhead. Adjusting the ATIM window size dynamically is accommodating to various traffic conditions for improving network throughput and reducing PS nodes' power consumption. The proposed protocol
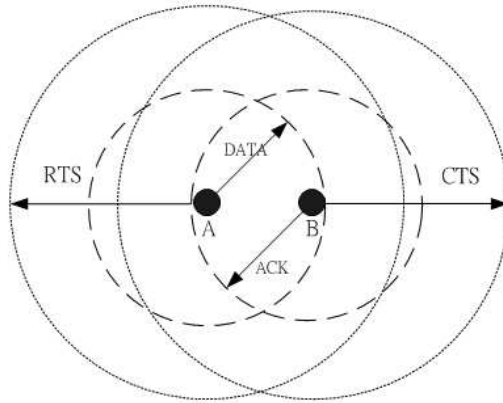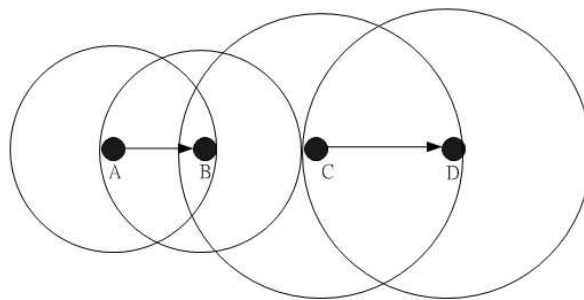
Figure 2.10: The Power Control Scheme

Figure 2.11: Differences in Transmit Power Lead to Increased Collisions

in [24] has two main contributions. First, it avoids unnecessary frame collisions and backoff waiting time in data frame transmissions. Second, it conserve more power of PS nodes and improve to the channel utilization, and develop a intelligent strategy to dynamically shorten the ATIM window size. It is clear that reducing nodes backoff idle time and avoiding frame collisions can improve energy efficiency and network throughput. In this protocol [24] define that a buffered data frames duration, called working duration, is piggy-backed in an ATIM frame. To minimize average waiting time, it follow shortest job first policy basically, so the node with the shortest total working duration have the highest priority to transmit its buffering frames. The total working duration of a node is the sum of the working durations of all ATIM frames related it. The protocol [24] has special mechanism, which allows a PS node can go back to sleep when it completes all its data transmissions. Each node constructs the transmission table by the information in ATIM frames. Next, the nodes determine the transmission order. This is the scheduling transmission mechanism in the protocol [24]. There is no bound for the ATIM window size at the beginning of the beacon interval, and the end of the ATIM window depends on the traffic load of ATIM frames. Each node can obtain the duration of frame transmissions by overhearing ATIM frames, and calculate the total duration of all its currently receiving ATIM frames. If nodes sense the channel is idle more than $T_{DIFS} + T_{CWmin}$, it deem that there will be no other node wanting to send ATIM frames. The ATIM window ends as illustrated in Fig. 2.12. If there is no any frame can be transmitted in the rest BI, all nodes end the current ATIM window immediately and enter the scheduled transmission as illustrated in Fig. 2.13.

Increasing spatial reuse is also a good way to reduce the energy consumption. As illustrated in Fig. 2.14, stations within the transmission range of A are all blocked due to the use of CSMA/CA mechanism when A is transmitting data to B with fixed power level. When A adjusts (decreases) its transmission power, some stations which is blocked by A will be released. Thus, C and D can transmit simultaneously when A is transmitting to B. Increasing spatial reuse is not only reducing power consumption but also increase the channel capture.

Above all, we know that the ATIM window size is relative to power consumption. When
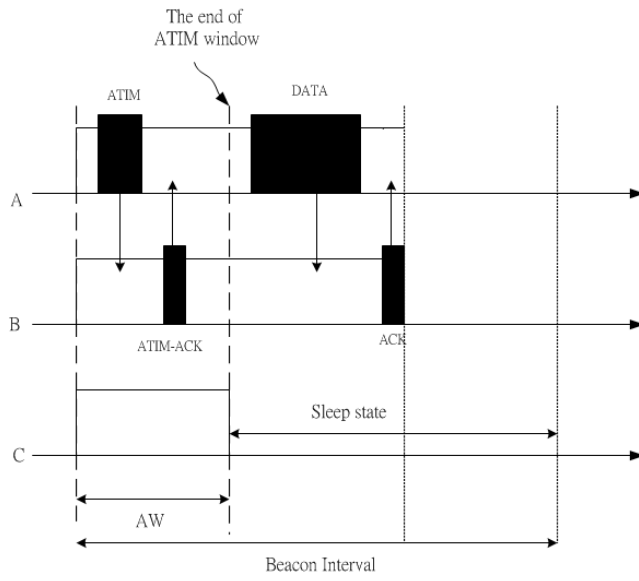
Figure 2.12: The First ATIM Period Ending Rule
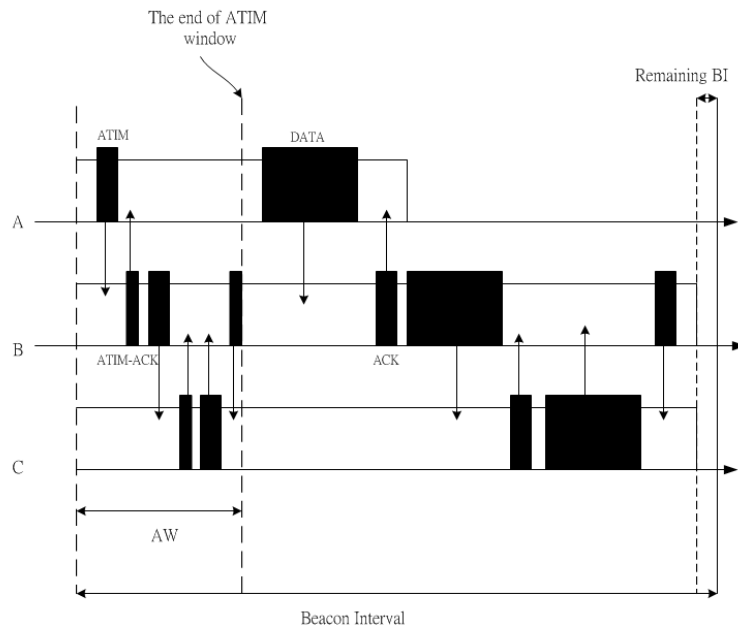
Figure 2.13: The Second ATIM Period Ending Rule
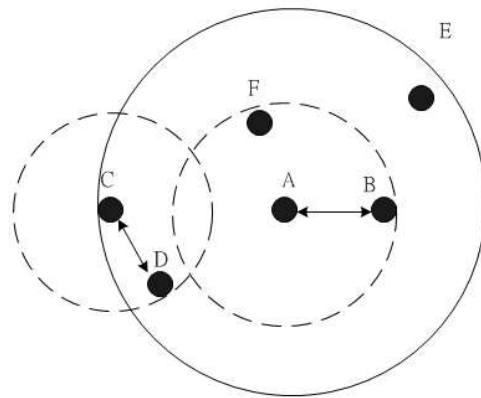
Figure 2.14: The Channel Capture Problem

the ATIM window size changes, the Beacon intervals should change. In this thesis, the analysis of beacon intervals will be discussed in next chapter.

Chapter 3

Analysis of Adaptable Beacon Intervals (ABIs)

Similar to the IEEE 802.11 PSM, synchronization between the MNs are assumed in this thesis. The synchronization signals can be obtained from a centralized control unit (e.g. Global Positioning System (GPS), Base Station, or Access Point (AP)) or a decentralized synchronization mechanism (e.g. mobile point coordinator). As shown in Fig. 3.1, the beacon packets are transmitted between the MNs at the beginning of each BI for synchronization purpose. The time interval for each BI (i.e. T_{BI}) is generally a pre-determined parameter in most of the wireless standards (e.g. $T_{BI} = 0.1$ ms for IEEE 802.11 PSM [2]). It can be more efficient to have adjustable T_{BI} based on certain network characteristics.

The concept of the Adaptable Beacon Interval (ABI) is to acquire feasible value of the ABI in order to effectively maintain system throughput and to reduce energy consumption. The following calculation and analysis are utilize to determine the reasonable value of T_{bi}.

3.1 IEEE 802.11's Timing Synchronization Function

Before calculating the adaptable beacon interval, we should know the relationship between beacon frames and IEEE 802.11's timing synchronization function. In the IEEE 802.11 PSM [2], MNs are required to be synchronous. In this section, IEEE 802.11's timing synchronization
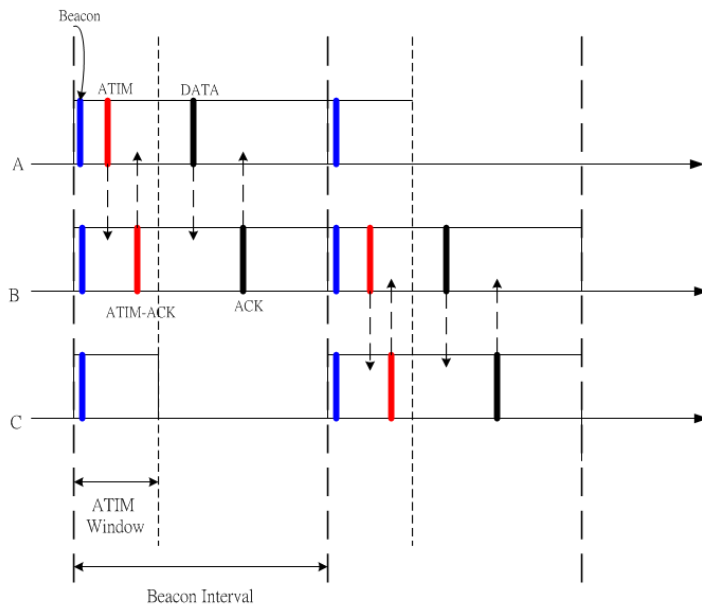
Figure 3.1: Nodes Send Beacons at the Beginning of BI
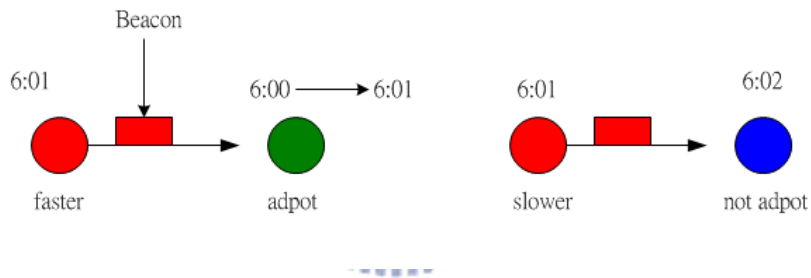
Figure 3.2: The MN Receives Beacon, Compares the Clock, and Modifies the Clock

function will be described.

In the IEEE 802.11 PSM, the time history is divided into beacon intervals, and each beacon interval contains a beacon generation window. Each MN waits for a random number of slots to transmit the beacon frame. Beacon frames are broadcast, which contain time-stamps. On receiving a beacon, the MN will adopts beacons timing only if $T(beacon) > T(MN)$ as shown in Fig. 3.2. So we can see that clocks only move forward, and faster clocks synchronize slower clocks. On the other hand, the time-stamps associated within the beacon frame will not be utilized if it is smaller than the time-stamps of the receiving MN.

3.2 The Analysis of Beacon Intervals (BIs)

A beacon interval consists of a beacon window (BW), an ATIM window, and the remaining BI. In the beacon window, beacon frames will be transmitted. The beacon window only takes several time slots in a beacon interval. While analyzing BIs, the beacon window can always be ignored. In the ATIM window, the ATIM frames and the ATIM-ACK frames will be transmitted. If MNs transmit or receive ATIM frames, they will be awake after ATIM window. On the other hand, if MNs do not transmit or receive ATIM frames, they will be sleep after the ATIM window to save energy. When receiving ATIM frames, MNs reply with ATIM-ACK frames. In the remaining BI, the RTS, CTS, data, and ACK frames will be transmitted.

Before analyzing the BIs, the following parameters are defined :

- t_{ATIM}: the transmission time of an ATIM frame

- $t_{ATIM-ACK}$: the transmission time of an ATIM-ACK frame

- t_{RTS}: the transmission time of a RTS frame

- t_{CTS}: the transmission time of a CTS frame

- t_{DATA}: the transmission time of a data frame

- t_{ACK}: the transmission time of an ACK frame

- t_B: the backoff time of transmitting packets

- $t_{collision-A}$: the waste time when ATIM frames collide or fail

- $t_{collision-D}$: the waste time when RTS frames collide or fail

- $t_{ATIM-timeout}$: the timeout if ATIM frame is transmitted

- $t_{RTS-timeout}$: the timeout if RTS frame is transmitted

- t_{SIFS}: the defer time of SIFS

27

- t_{DIFS}: the defer time of DIFS

- T_{AW}: the duration of the ATIM window

- T_{RBI}: the duration of the remaining BI

- T_{ABI}: the duration of Adaptable Beacon Interval (ABI)

- T_{BI}: the duration of a BI

- T_A: the time of one transmission pair including the ATIM and ATIM-ACK frames

- T_D: the time of one transmission pair including the RTS, CTS, data, and ACK frames

- $P_{collision}$: the probability of collision

In the IEEE 802.11 PSM [2], the beacon interval consists of the ATIM window and the remaining BI as :

$$T_{BI} = T_{AW} + T_{RBI} \tag{3.1}$$

If we want to conserve more energy, a data frame should be transmitted in a beacon interval. It means that only an ATIM frame and an ATIM-ACK frame will be transmitted in a ATIM window. Certainly, a RTS, a CTS, a data, and an ACK frame will be transmitted in the remaining BI. As shown in Fig. 3.3 (a) and (b), the length of BI is different. The length in Fig. 3.3 (b) is twice as long as the length in Fig. 3.3 (a). In Fig. 3.3, node A transmits data packets to node C via node B, and node D transmits data packets to node F via node E. It allows that only a transmission pair including an ATIM, an ATIM-ACK, a RTS, a CTS , a data, and an ACK frame in Fig. 3.3 (a) because the length of BI is limited. For example as in Fig. 3.3 (a), node A transmits the packet to node B in the first BI. In Fig. 3.3 (b), two transmission pairs can be allowed in one BI. Node A transmits the packet to node B, and node D transmits the packet to node E in the same BI. We assume that the power consumption for one node in one BI as in Fig. 3.3 (a) is P. So we know that the power consumption for one node in one BI in Fig. 3.3 (b) is $2P$ because the length of BI is twice.

The total power consumption is $8P$ in Fig. 3.3 (a), and the total power consumption is $16P$ in Fig. 3.3 (b). The power consumption is less if there is only one transmission pair in one beacon interval.

We define the power in one BI which allows one transmission pair is P_{BI_1}. If the BI allows n transmission pairs, the power consumption is nP_{BI_1}. We can get the difference of power consumption (ΔP) in n BI :

$$\Delta P = 2n^2 P_{BI_1} - 2n P_{BI_1} \tag{3.2}$$

Although the duration of one BI is reduced for energy conservation purpose, the control packets are increased. In the beginning of BI, the beacons will be transmitted. We assume that T_{beacon} is the duration of beacon window. The numbers of control packets (ΔC) will increase, and may cause some delay time (ΔT_c):

$$\Delta C = n^2 - n \tag{3.3}$$

$$\Delta T_c = (N - 1)T_{beacon} \tag{3.4}$$

The minimum time interval for T_{AW} and T_{RBI} to transmit n successful pairs of data can be represented as :

$$T_{AW} = nT_A + T_{beacon} \tag{3.5}$$

$$T_{RBI} = n \cdot T_D + \delta \tag{3.6}$$

The δ is a modifying parameter. Because of different conditions, the δ will be different. In this thesis, the δ is ignored.

In IEEE 802.11, the numbers of transmission pairs (n) is calculated as :

$$n = \frac{T_{BI} - T_{AW}}{T_D} = \frac{T_{AW} - T_{beacon}}{T_A} \tag{3.7}$$

29
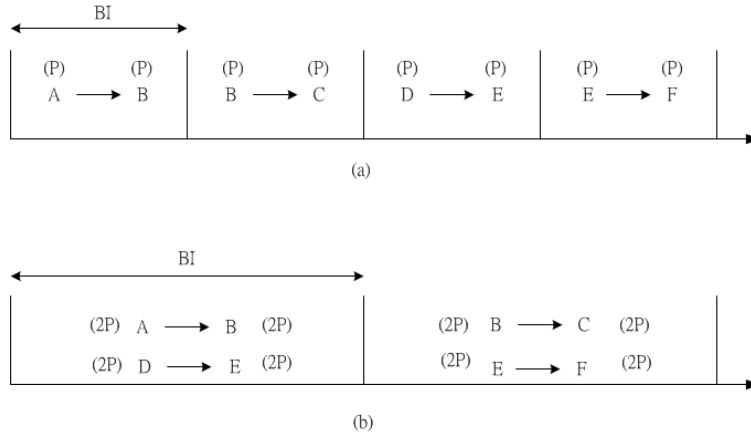
Figure 3.3: Different Length of BI

The accurate length of BI for one transmission pair is hard to calculated because of the random backoff and the happening of collision. We can calculate the mean of collision time $(E[t_{collision-A}], E[t_{collision-D}])$ and the mean backoff time $(E[t_B])$ to obtain the length of BI for one transmission pair.

As illustrated in Fig. 3.4, we can obtain the length of T_D is :

$$T_D = E[t_B] + t_{DIFS} + t_{RTS} + t_{SIFS} + t_{CTS} + t_{SIFS} +$$
$$t_{DATA} + t_{SIFS} + t_{ACK} + t_{DIFS} + E[t_{collision-D}] \qquad (3.8)$$

The same as RTS and CTS packets exchange, so the length of T_A is :

$$T_A = E[t_B] + t_{DIFS} + t_{ATIM} + t_{SIFS} + t_{ATIM-ACK} + t_{DIFS} + E[t_{collision-A}] \qquad (3.9)$$

For power-saving purpose, the T_{AW} should be equal to T_A, and the T_{RBI} should be equal to T_D.

$$T_{AW} = T_A \qquad (3.10)$$

$$T_{RBI} = T_D \qquad (3.11)$$

$$T_{ABI} = T_A + T_D \qquad (3.12)$$

30
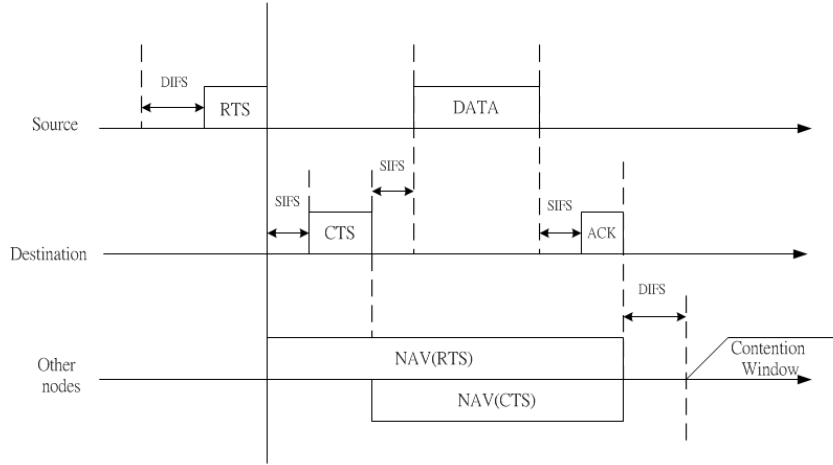
Figure 3.4: The Defer Mechanism in IEEE 802.11

3.3 The Relationship between The Probability of Collision and Neighbor nodes

In this section, we have to calculate the mean of collision time. First, the probability of collision should be found. According to [25], it proposes that there are two kinds of the probability of collision. One is that the probability P_1 for multiple nodes to transmit RTS packets during the same time slot :

$$P_1 = \sum_{i=2}^{\infty} [1 - (1 - p')^i - ip'^{(i-1)}]\frac{M^i}{i!}e^{-M}$$
$$= 1 - (1 + Mp')e^{-p'M} \qquad (3.13)$$

, where M is the mean number of nodes that belong to the shared channel, and p' is the probability that a node transmits in a time slot.

The other is that the probability P_2 for one node around the channel to initiate a failed handshake with a node outside the region. Even though a CTS packet may not be sent due

31

to the collision of the sending nodes RTS packet with other packets :

$$P_2 = 1 - e^{-p'M} - p_s M e^{-p'M} - (1 - (1 + Mp')e^{-p'M})$$

$$= (p' - p_s)Me^{-p'M} \tag{3.14}$$

, where p_s is the probability that a node begins a successful four-way handshake at each slot.

The two equations have some unknown parameters. In [25], the mean number of nodes that belong to the shared channel is $M = \lambda \pi R'^2 = \alpha^2 N$ where $N = \lambda \pi R^2$. N is the average number of nodes within a circular region of radius R. It obtain $R' = \alpha R$ where $0.5 \leq \alpha \leq 2$, and α need to be estimated. In this thesis, we assume $\alpha = 1$. The throughput is relative to the different p', and p' is also relative to the data arrival rate from upper layer down to MAC layer. According to his simulation, we assume $p' = 0.1$ in order to get good throughput. The parameter p_s denotes the probability that a node begins a successful four-way handshake at each slot. In [25], a equation is used to calculate the parameter p_s, but the equation is complex. We can find that p' is the probability which a node transmits in a time slot, and the p_s is less than p'. So we assume that $p_s = 0.05$, the half of p'. The total probability of collision $P_{collision}$ becomes :

$$P_{collision} = P_1 + P_2 = 1 - (1 + Mp')e^{-p'M} + (p' - p_s)Me^{-p'M}$$

$$= 1 - e^{-p'N} - p_s N e^{-p'N}$$

$$= 1 - e^{-0.1N} - 0.05 N e^{-0.1N} \tag{3.15}$$

The probability of collision will be simplified, and it is relative to the number of neighbor nodes. As illustrated in Fig. 3.5, x-axis is the number of neighbor nodes (N), and y-axis is the probability of collision ($P_{collision}$).
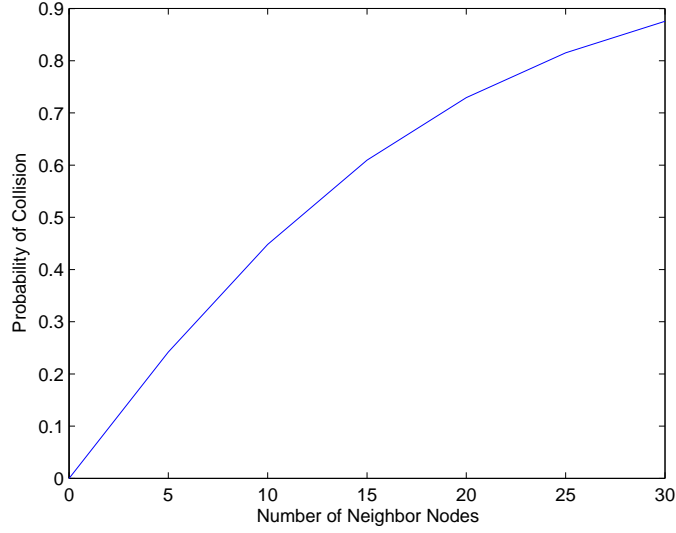
Figure 3.5: The Relationship between the Probability of Collision ($P_{collision}$) and the Number of Neighbor Nodes (N)

3.4   The Calculation of Adaptable Beacon Intervals (ABIs)

In this section, we can calculate the beacon interval, which is adaptable to the number of neighbor nodes. As mentioned in (3.8) and (3.9), we will describe how to calculate $E[t_{collision-D}]$ and $E[t_{collision-A}]$. In the IEEE 802.11, the ATIM frame can be retransmitted three times if it fails. So the mean value of collision time of an ATIM frame is :

$$E[t_{collision-A}] = P_{collision}(E[t_B] + t_{ATIM-timeout} + t_{ATIM})$$
$$+ P^2_{collision}(2E[t_B] + t_{ATIM-timeout} + t_{ATIM})$$
$$+ P^3_{collision}(4E[t_B] + t_{ATIM-timeout} + t_{ATIM}) \qquad (3.16)$$

And the RTS frame can be retransmitted seven times if it fails. So the mean value of collision time of a RTS frame is :

$$
\begin{aligned}
E[t_{collision-D}] = \ &P_{collision}(E[t_B] + t_{RTS-timeout} + t_{RTS}) \\
&+P_{collision}^2(2E[t_B] + t_{RTS-timeout} + t_{RTS}) \\
&+P_{collision}^3(4E[t_B] + t_{RTS-timeout} + t_{RTS}) \\
&+P_{collision}^4(8E[t_B] + t_{RTS-timeout} + t_{RTS}) \\
&+P_{collision}^5(16E[t_B] + t_{RTS-timeout} + t_{RTS}) \\
&+P_{collision}^6(16E[t_B] + t_{RTS-timeout} + t_{RTS}) \\
&+P_{collision}^7(16E[t_B] + t_{RTS-timeout} + t_{RTS})
\end{aligned}
\tag{3.17}
$$

In this thesis, our adaptable beacon intervals (ABIs) is different according to the number of neighbor nodes. Above all, We conclude that the duration of ABIs is :

$$
\begin{aligned}
T_{ABI} = T_{AW} + T_{RBI} = T_A + T_D = \ &E[t_B] + t_{DIFS} + t_{ATIM} \\
&+t_{SIFS} + t_{ATIM-ACK} + t_{DIFS} + E[t_{collision-A}] \\
&+E[t_B] + t_{DIFS} + t_{RTS} + t_{SIFS} + t_{CTS} + t_{SIFS} \\
&+t_{DATA} + t_{SIFS} + t_{ACK} + t_{DIFS} + E[t_{collision-D}]
\end{aligned}
\tag{3.18}
$$

It is noted that the calculation of ABIs will be used in the proposed Intelligent Router-Assisted (IRouter) power saving medium access control algorithm in the next chapter. Therefore, we can save more power. The parameter of the Equation 3.19 is shown in Table 1.

TABLE 1

PARAMETERS

Parameter Name	Parameter Value
t_{ATIM}	0.000416(s)
$t_{ATIM-ACK}$	0.000416(s)
t_{RTS}	0.000352(s)
t_{CTS}	0.000304(s)
t_{DATA}	0.008(s)
t_{ACK}	0.000304(s)
t_{DIFS}	0.00005(s)
t_{SIFS}	0.00001(s)
$t_{ATIM-timeout}$	0.000846(s)
$t_{RTS-timeout}$	0.00067(s)

After calculating the duration of ABIs, we have to decide how many transmission pairs in one beacon interval. As described in section 3.2, one transmission pair in one beacon interval can save power, but cause beacon frames overhead. The overhead of beacon frames may cause the problem of timing synchronization. We assume that X transmission pairs can be in one BI (means $T_{BI} = X \cdot T_{ABI}$), P is the power for one transmission pair, and total numbers of MNs is N in the area. The power consumption (P_{total}) is :

$$P_{total} = XP\{(X+1)Q(\frac{N-1}{X}) + [R(\frac{N-1}{X}) + 1]\} \tag{3.19}$$

, where $Q(x)$ is the quotient of x, and $R(x)$ is the remainder of x.

The numbers of control packets (C) will be :

$$C = [Q(\frac{N-1}{X}) + 1] \cdot N \qquad if \quad R(\frac{N-1}{X}) \neq 0 \tag{3.20}$$

$$= Q(\frac{N-1}{X}) \cdot N \qquad if \quad R(\frac{N-1}{X}) = 0 \tag{3.21}$$

$$\tag{3.22}$$
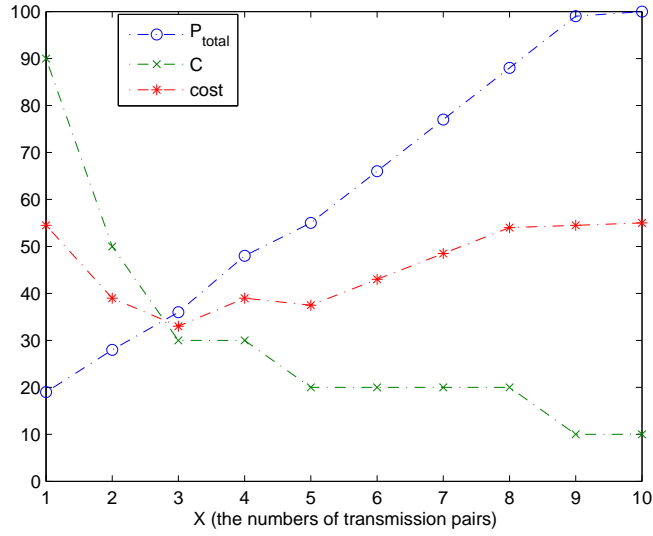
Figure 3.6: P_{total} , C, and the Cost Function ($cost$)
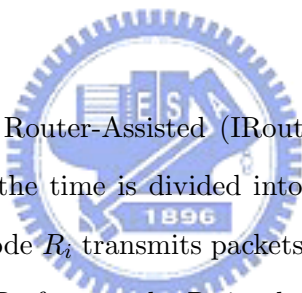
There is tradeoff between the power consumption and the numbers of control packets. So a cost function will be defined:

$$cost = w_1 \cdot P_{total} + w_2 \cdot C \qquad (3.23)$$

The parameter of w_1 is the weight of power, and the w_2 is the weight of numbers of control packets. If we chose $w_1 = 0.5$ and $w_2 = 0.5$, we can find the minimum cost and the X value will also be found. For example, the total numbers of MNs (N) is 10, and $w_1 = w_2 = 0.5$. As shown in Fig. 3.6, the minimum of cost can be found when $X = 3$. So we can decide the duration of one BI ($T_{BI} = X \cdot T_{ABI}$) by the X, which are calculated according to the cost function.

Chapter 4

The Intelligent Router-Assisted (IRouter) Power Saving Medium Access Control Algorithm

In this chapter, the Intelligent Router-Assisted (IRouter) power saving MAC algorithm is proposed. In IEEE 802.11 [2], the time is divided into units of beacon interval in order to save power. For example, the node R_i transmits packets to node R_k via node R_j, the packets must be transmitted to node R_j from node R_i in the first BI. The same packets will be transmitted from node R_j to node R_k in the next BI. We can see that if node R_j and node R_k don't contend for the channel in the next BI, the delay time will increase. The basic idea of IRouter is that the packets can be sent to destination early . The proposed IRouter scheme incorporates partial routing information within the power-saving MAC protocol design. Based on the partial routing information, multi-hop packet delivery can be achieved within a single beacon interval as illustrated in Fig. 4.1. We find that IRouter also can reduce the power consumption and get good throughput.
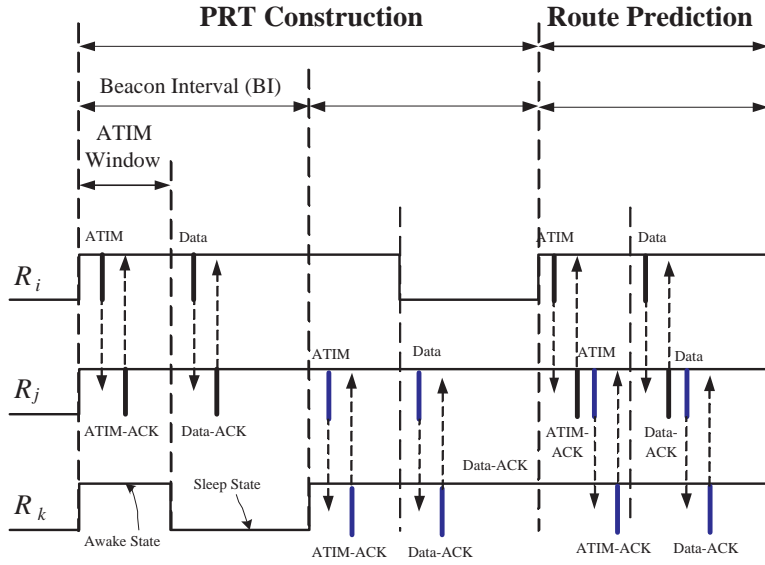
Figure 4.1: The Timing Diagram of the IRouter Scheme

4.1 Assumptions and Concepts

There is tradeoff between the computational power of the MNs and the communication bandwidth for data transmission. With the advancement of processing capability and memory technology, the mobile devices are more likely to possess higher memory footprints and processing power. Without extending the size of the control packets for data transmission, the proposed IRouter scheme generates tables within the cache memories of the mobile devices. The communication bandwidth for data transmission can therefore be preserved with the proposed algorithm. In additions, the proposed IRouter MAC algorithm is designed to be independent to the routing layer protocols. Different types of ad hoc routing algorithms can be applied on top of the IRouter scheme.

There are two processes in IRouter Algorithm. One is PRT Construction Process, and the other is Route Prediction Process. The PRT is the Partial Route Table, which each node will generate with the cache memories. The PRT is used to record some routing information in MAC layer. In PRT Construction Process, each node will record its upstream and downstream node in PRT. In Route Prediction Process, each node can transmit packets to the destination fast by the information of PRT as shown in Fig. 4.1.

In Fig. 4.1, we can consider that the PRT Construction Process is the IEEE 802.11 PSM, and the Route Prediction Process is IRouter scheme. In first BI, the node R_i and R_j are awake, and node R_k is sleep. In second BI, the node R_j and R_k are awake, and node R_i is sleep. In the two BIs, the number of awake nodes is four. Let's see IRouter scheme. Node R_i, R_j, and R_k are awake in the first BI, but the three nodes are sleep in the second BI because the packets transmit to the destination R_k. The number of awake nodes is three in the same two BIs. So we see that the IRouter scheme can reduce the power consumption.

4.2   The IRouter Algorithm

In the IRouter algorithm, the MNs within the network topology can be classified based on their functionalities, i.e. $\mathbf{N} = \{\mathbf{S}, \mathbf{D}, \mathbf{R}, \mathbf{I}\} = \{S_i, D_i, R_i, I_i \mid 1 \leq i \leq n\}$. $\mathbf{S}$ represents the set of source MNs that initiate data packet transmission; $\mathbf{D}$ contains the destination MNs that only receive data packets; $\mathbf{R}$ encloses the MNs that redirect the data packets between nodes S_i and D_i; $\mathbf{I}$ is the set of inactive MNs. It is noted that the router node R_i for one route is also capable of being the data source or destination for other routes within the network. The functionality of each MN will be defined based on its Partial Route Table, PRT, which will be explained in the following.

The concept of the proposed IRouter scheme is based on the high probability that same routes will be utilized for delivering more than a single data packet. Partial routing information, including the previous and the next hopping nodes, is recorded in a cache memory within the router MNs, i.e. R_i.

Fig. 4.2 shows an example of network topology that utilizes the proposed IRouter scheme. There are three different routes $(\Gamma_1, \Gamma_2, \Gamma_3)$ that are partially illustrated in the network topology in consideration, i.e. $\Gamma_1 = \{\ldots, R_h, R_i, R_j, R_k, R_l, \ldots\}$, $\Gamma_2 = \{S_i, R_j, R_x, \ldots\}$, $\Gamma_3 = \{\ldots, R_y, D_i\}$. In order to justify the proposed scheme, the route between nodes R_i, R_j, and R_k and their associated transmission range circles are the primary concerns in this thesis.

It is noted that the determination of the multi-hop sequences within a route are conducted by the routing layer protocols. The MAC layer algorithm within a router node is aware of
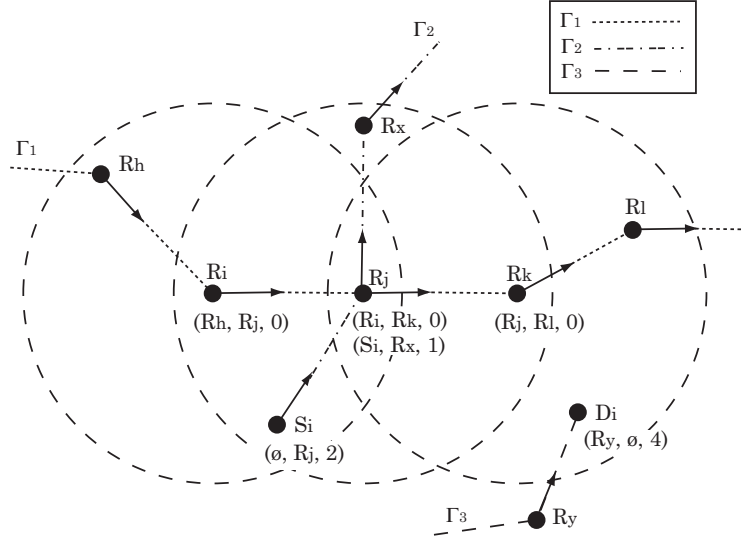
Figure 4.2: The Network Topology with the Proposed IRouter Scheme

the information of its next delivering MN only if the following steps are fulfilled:

1. the data packet has arrived in the MN;

2. based on the information obtained from the received data packet, the routing protocol determines its next forwarding MN within the route;

3. the information is forwarded to the MAC layer algorithm to schedule for the data transmission.

The design concept of the proposed IRouter scheme is to predict the next hopping MN before the actual arrival of the data packet. During the time interval for ATIM handshaking, the predicted next delivering MN (obtained from the information recorded in the PRT) is requested to be in the awake state for potential data transmission. The Partial Route Table, $PRT = \langle ENT_1, ENT_2, \ldots \rangle$, created within the cache memory of each MN is utilized to record partial routing information. The three fields within each entry $ENT_i = (UpMN, DownMN, TTL)$ of the PRT is explained as follows:

1. $UpMN$: The first field within each PRT entry indicates the upstream MN within the route.

2. *DownMN*: The second field in each *PRT* entry designates the downstream MN of the route.

3. *TTL*: The Time-To-Live (*TTL*) field is utilized to represent the freshness of the corresponding *PRT* entry. The smaller *TTL* value indicates the more up-to-date information is recorded in the previous two fields. While *TTL* is equal to zero, the *PRT* entry contains the newly updated upstream and downstream information.

The *PRT* of R_j is obtained as $PRT_{R_j} = \langle (R_i, R_k, 0), (S_i, R_x, 1) \rangle$, which indicates that R_j is a router node for the two different routes, Γ_1 and Γ_2, as the example illustrated in Fig. 4.2. The first entry illustrates that node R_j has R_i as its upstream MN; while R_k is the corresponding downstream MN. It is noted that $TTL = 0$ represents that the most up-to-date information is recorded in this entry. The second entry shows that node R_j also has S_i as its upstream MN in the route Γ_2; while R_x is the downstream MN (with $TTL = 1$). The *PRT* within the source node S_i is obtained as $PRT_{S_i} = \langle (\phi, R_j, 1) \rangle$, where ϕ indicates that the source node S_i does not have a upstream MN within the route Γ_2. The *PRT*s within other MNs (as shown in Fig. 4.2) can also be observed in the similar manners.
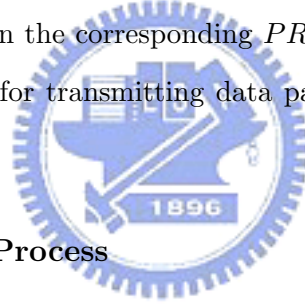
The proposed IRouter scheme consists of two processes, including the *PRT* construction and the route prediction processes. The route prediction process forecasts the next hopping MN based on the information obtained from the *PRT* construction process. The proposed algorithm is described in the following two subsections:

4.2.1 *PRT* Construction Process

As shown in Figs. 4.1 and 4.2, the data packets are assumed to be transmitted from node R_i, via R_j, to R_k. All the MNs within the neighborhood of node R_i are synchronized at the beginning of the BI and stay in the awake state during the entire ATIM window. Other MNs within the communication range (i.e. nodes R_h, R_j, and S_i) may intend to compete the time slot for transmitting its packets in queue. It is assumed that node R_i wins the channel contention and sends out an ATIM frame requesting for the data transmission. In this example, the destination node ID within this ATIM frame is designated as node R_j. Node

R_j replies with an ATIM-ACK frame to R_i; while other MNs discard this ATIM frame after receiving it (e.g. nodes R_h, R_j, and S_i). Node R_j records the ID of the upstream node in one of its PRT_{R_j} entries (i.e. the ID of node R_i as shown in Fig. 4.2). The TTL value in the corresponding entry is reset to zero. After receiving the ATIM-ACK frame from node R_j, node R_i also records the ID of R_j as the $DownMN$ in one of its PRT_{R_i} entries.

After the ATIM window is finished, node R_i initiates the transmission of data packet to node R_j. In additions, only nodes R_i and R_j are in the awake state after the ATIM window as shown in Fig. 4.1. For power-saving purpose, the power mode of other MNs are in the sleep state, which will not be able to either transmit or receive data packets until the next BI starts. Since the data packets are assumed to be routed from node R_i, via R_j, to R_k, the transmission from node R_j to R_k follows similar procedures as that from node R_i to R_j. As can be seen from Fig. 4.2, several fields within the PRT_{R_j} and PRT_{R_k} are filled (i.e. the ID of R_k is recorded in the $DownMN$ field in the corresponding PRT_{R_j} entry; the ID of R_j is inserted into the $UpMN$ field in the corresponding PRT_{R_k} entry). The power states within the PRT construction process for transmitting data packets can also be observed from the timing diagram as in Fig. 4.1.

4.2.2 Route Prediction Process

The effectiveness of the proposed IRouter scheme can be examined from the route prediction process of the algorithm. The concept of the algorithm is based on the high probability that the same route should be utilized for delivering more than a single data packet. For instance, there is high possibility to deliver the remaining data packets using the same route from node R_i, via R_j, to R_k. After the PRT construction process, some of the MNs pertain certain information in their PRTs as shown in Fig. 4.2. Within the routing layer protocol, it is assumed that another data transmission from node R_i, via R_j, to R_k is decided. The IRouter algorithm of node R_i is requested for the packet delivery to node R_j at the beginning of the third BI (as shown in Fig. 4.1). Node R_i sends out an ATIM frame, which is destined to node R_j, to its neighborhood MNs. After receiving the ATIM frame from node R_i, R_j replies with

an ATIM-ACK frame to R_i for acknowledgement.

One of the major characteristics of the proposed IRouter scheme is that each MN will verify its PRT after sending out the ATIM-ACK frame to the corresponding requestor. As shown in the route prediction process as in Fig. 4.1, node R_j continues to verify if there is any routing information existed within its PRT_{R_j} after sending the ATIM-ACK frame to node R_i. Based on the information from the $PRT_{R_j}(R_i, R_k, 0)$ entry within node R_j, it is recognized that R_k has high possibility to be the next hopping node within the route. Node R_j will initiate an ATIM frame to node R_k within the same ATIM window as shown in Fig. 4.1. It is noticed that there can be many MNs competing for sending their ATIM frames (e.g. nodes R_h, R_j, and S_i as in Fig. 4.2) within the same ATIM window.

After receiving the ATIM frame from node R_j, R_k replies with an ATIM-ACK for hand-shaking. Similar route checking mechanism continues at node R_k to determine if there is another next hopping node within the route. Based on the information obtained from the PRT of each MN, additional pairs for ATIM/ATIM-ACK handshaking can be delivered within the same ATIM window as the length of the window permits.

After the time for the ATIM window elapse, nodes R_i, R_j, and R_k are requested to be in the awake state; while other MNs are set to the sleep state. Within the remaining time interval of the same BI, nodes R_i and R_j conduct Data/Data-ACK handshaking for data transmission. After receiving the data packet from node R_i, the actual packet transmission from node R_j to R_k will be verified by the routing layer protocol. The IRouter scheme of node R_j forwards the data packet to its upper layer routing algorithm for the determination of the next hopping MN. Assuming that $\mathbf{P}_{down}^{R_j}\langle P, N\rangle$ represents the common packet header acquired from node R_j's routing algorithm down to the IRouter MAC scheme, where P indicates the previous hopping node; and N stands for the next hopping node as shown in Fig. 4.3. If it is observed that $P = R_i$, there can be two different cases occurred depending on the values within the $PRT_{R_j}(R_i, R_k, 0)$ and $\mathbf{P}_{down}^{R_j}\langle P, N\rangle$:

- If $N = R_k$, it indicates that the routing decision within node R_j determines to forward the data packet from R_j to R_k. Node R_j can perform the packet delivery to node R_k
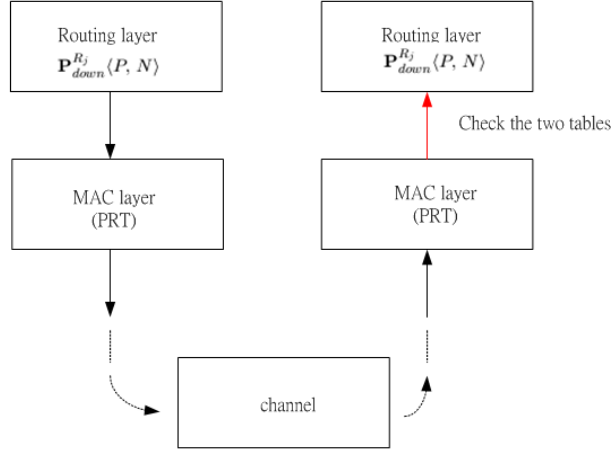
Figure 4.3: The IRouter MAC Scheme Will Check the PRT and $\mathbf{P}_{down}^{R_j}\langle P, N\rangle$

within the same BI since R_k is the predicted $DownMN$ with awaked power state. The same prioritized contention mechanism as in (**??**) is utilized to ensure that the data packet is delivered with relatively higher priority.

- If $N \neq R_k$, the routing decision within node R_j designates that the data packet from node R_i should be forwarded to node N, which is different from the $DownMN$ field of the $PRT_{R_j}(R_i,\ R_k,\ 0)$. There will be no further data transmission from node R_j to either node R_k or N within this BI since the power state of node N is unknown at this point. The $PRT_{R_j}(R_i,\ R_k,\ 0)$ will be modified as $PRT_{R_j}(R_i,\ N,\ 0)$ to reflect the new update from the routing decision. Until the next BI starts, the ATIM/ATIM-ACK handshaking will be performed between nodes R_j and N to wake up both MNs for data transmission.

It is noticed that there are chances that the IRouter algorithm within node R_j may not receive indication from its routing layer protocol for a pre-specified time interval. It implies that the data packet should not be forwarded to node R_k based on the routing decision. The $PRT_{R_j}(R_i,\ R_k,\ 0)$ will be changed to $PRT_{R_j}(R_i,\ \emptyset,\ 0)$, which indicates that no further data forwarding is required.

As was mentioned previously, the TTL value in each PRT entry is utilized to show the

freshness of its associated partial route. The update scheme for the TTL value is as follows. If it is found that the next hopping MN matches with the predicted $DownMN$ during the route prediction process (i.e. $N = R_k$), the TTL value will be reset to zero to represent the up-to-date information in the corresponding PRT entry. The TTL value in each entry will be increased by one at the beginning of each BI. If the TTL value is greater than a pre-specified value η, the corresponding PRT entry will be discarded. It indicates that the information stored in the PRT entry is comparably out-of-date for the MN to adopt. Based on the route prediction mechanism of the proposed IRouter scheme, the data packet can be routed between more than two MNs within a single BI. In the next section, the effectiveness of the IRouter algorithm will be examined in simulations.

Chapter 5

Performance Evaluation

The performance of the proposed IRouter algorithm is evaluated via simulations. The Network Simulator (ns-2, [26]) is utilized to implement the proposed scheme and to compare with other existing MAC protocols, including the IEEE 802.11 with the Active Mode (AM) and with the Power Saving Mode (PSM). A number of ad hoc routing protocols have been developed for the MANETs. The topology-based routing protocols can be categorized into proactive (such as DSDV [27] and WRP [28]) and reactive algorithms (such as AODV [29], DSR [30], TORA [31], ABR [32], and SSA [33]). The AODV [29] protocol is adopted as the routing mechanism to perform the comparison between these MAC layer algorithms.

5.1   Simulation Parameters

The parameters utilized in the simulations are listed as shown in the Table 2.

TABLE 2

SIMULATION PARAMETERS

Parameter Type	Parameter Value
Simulation Area	400 × 400 m
Simulation Time	100 sec
Transmission Range	100 m
Pause Time of MN	5 sec
Traffic Types	Constant Bit Rate (CBR)
Size of Data Packet	1024 Bytes
ATIM Frame Size	18 Bytes
ATIM-ACK Frame Size	18 Bytes
Data-ACK Frame Size	15 Bytes
Idle Power State	0.50 Watt
Transmitting Power State	1.60 Watt
Receiving Power State	1.20 Watt
Sleep Power State	0.066 Watt

5.2   Simulation Results

Three different types of ad hoc MAC protocols, the proposed IRouter scheme, the 802.11 with the AM and with the PSM, have been implemented in the simulations. The TTL threshold η is selected as 1.0 sec. Three network topology are used in the simulations. In first and second network topology, nodes are fixed, and the numbers of multi-hops are known. We can decide the value of parameter X (numbers of transmission pairs in one BI) with the numbers of multi-hops. In the third network topology, nodes move randomly, we will decide the value of parameter X by the cost function, which is defined before. The following four metrics are utilized for performance comparison:

1. The Average Remaining Energy: The average power left for the MNs after the packet

Figure 5.1: The Network Topology 1 (Three Fixed Nodes; One Source Node, One Router Node, and One Destination Node)

transmission.

2. The Data Packet Delivery Ratio: The percentage of successful deliveries for the data packets.

3. The End-to-End Delay: The average time elapsed for delivering a data packet from the transmitter to the receiver.

4. Control Packet Overhead: The ratio between the total numbers of control packets and the total numbers of the received data packets.

5.2.1 Topology 1 (three fixed nodes; one source node, one router node, and one destination node)

The network topology 1 is shown in Fig. 5.1. Because only one node is sender, the problem of collision doesn't happen. The mean of collision time will be ignored. The $T_A = 0.0013$ and $T_D = 0.0094$. We use two times of ABIs in this case ($X = 2$, two hops), so the $T_{BI} = 2 \times (T_A + T_D) = 0.0214$; $T_{AW} = 2 \times T_A = 0.0026$.

As can be seen from Fig. 5.2 for the average remaining energy of the MNs, the proposed IRouter scheme can achieve better energy conservation comparing with the other two algorithms. The three node are fixed, so the delivery ratio is very close between 802.11 PSM and the IRooter scheme as shown in Fig. 5.3. The IRouter algorithm improve the end-to-end delay than 802.11 PSM as shown in Fig. 5.4. It can be observed from Fig. 5.5 that the control packet overhead of the IRouter is comparably less than that from the 802.11 PSM.
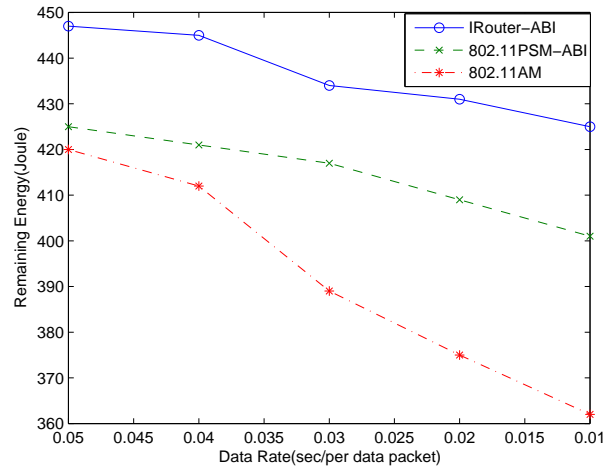
48

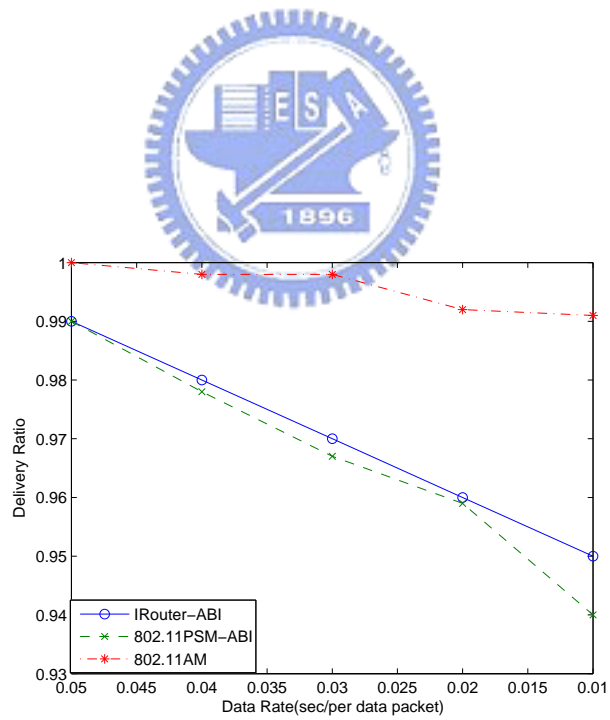Figure 5.2: Performance Comparison: Remaining Energy vs Data Rate

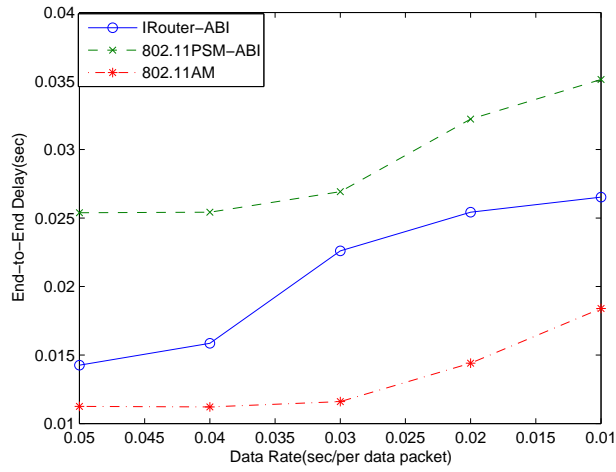Figure 5.3: Performance Comparison: Packet Delivery Ratio vs Data Rate

Figure 5.4: Performance Comparison: End-to-End Delay vs Data Rate
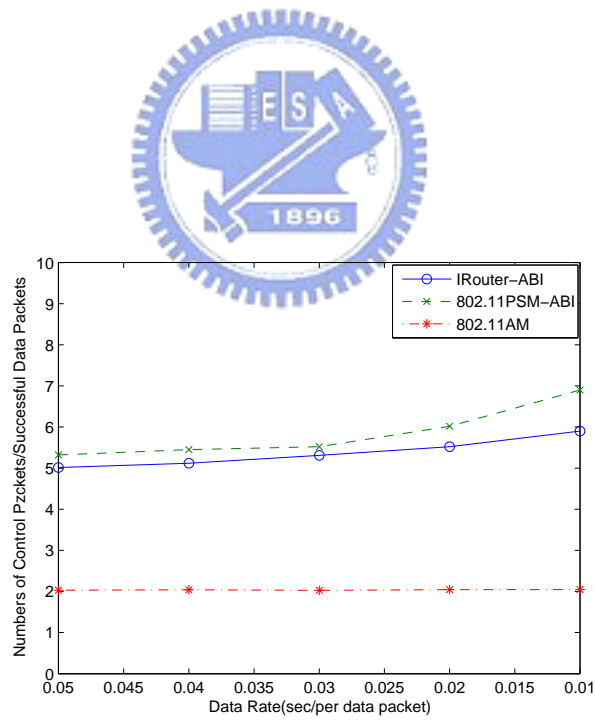

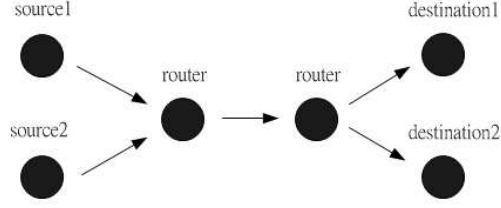Figure 5.5: Performance Comparison: Control Packet Overhead vs Data Rate

Figure 5.6: The Network Topology 2 (Six Fixed Nodes; Two Source Nodes, Two Router Nodes, and Two Destination Nodes)

5.2.2 Topology 2 (six fixed nodes; two source nodes, two router nodes, and two destination nodes)

Fig. 5.6 shows the network topology 2. The same as network topology 1, the probability of collision is very small. The mean of collision time can be ignored, too. We use three times of ABIs in this case ($X = 3$, three hops), so the $T_{BI} = 3 \times (T_A + T_D) = 0.0321$; $T_{AW} = 3 \times T_A = 0.0039$.

The proposed IRouter scheme can achieve better energy conservation comparing with the other two algorithms, as can be seen from Fig. 5.7 for the average remaining energy of the MNs. The nodes are fixed, so the delivery ratio is very close between 802.11 PSM and IRooter scheme as shown in Fig. 5.8. The IRouter algorithm improve the end-to-end delay than 802.11 as shown in Fig. 5.9. It can be observed from Fig. 5.10 that the control packet overhead of the IRouter is comparably less than that from the 802.11 PSM.

5.2.3 Topology 3 (random way points)

The random way point model is utilized as the mobility model for the MNs in the simulations.

The total nodes (N_{total}) are from 24 to 104 ($N_{total} = 24, 44, 64, 84, 104$) according to the number of neighbor nodes (N_{nei}) ($N_{nei} = 5, 10, 15, 20, 25$).

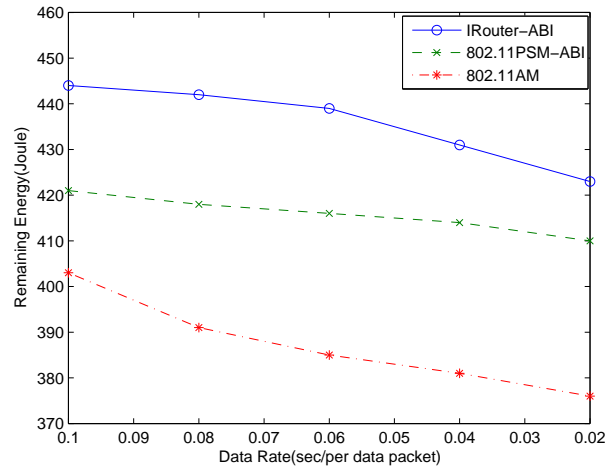$$N_{total} = (N_{nei} + 1)\frac{S^2}{d^2} \tag{5.1}$$

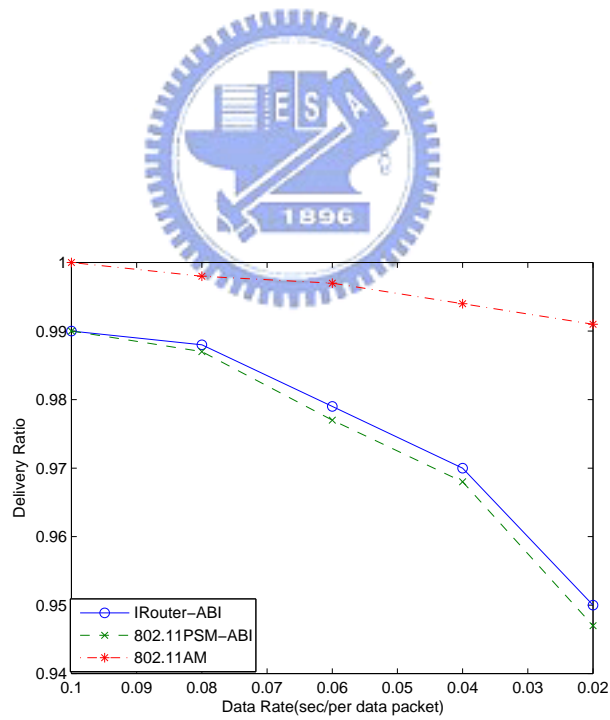Figure 5.7: Performance Comparison: Remaining Energy vs Data Rate

Figure 5.8: Performance Comparison: Packet Delivery Ratio vs Data Rate
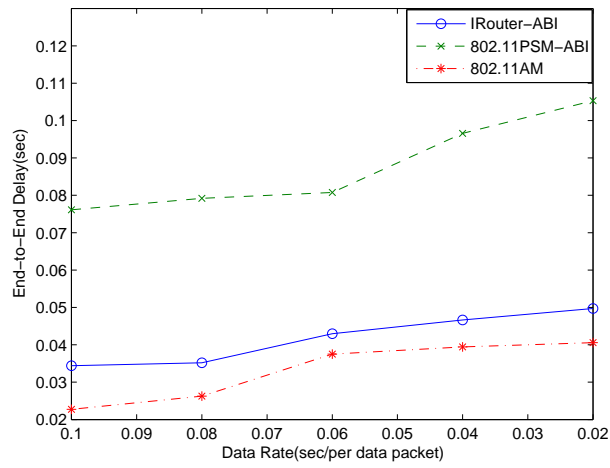
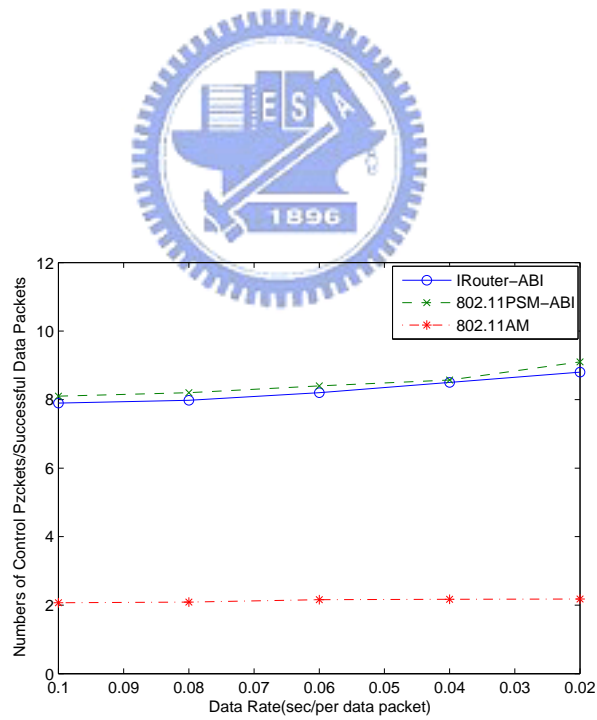Figure 5.9: Performance Comparison: End-to-End Delay vs Data Rate

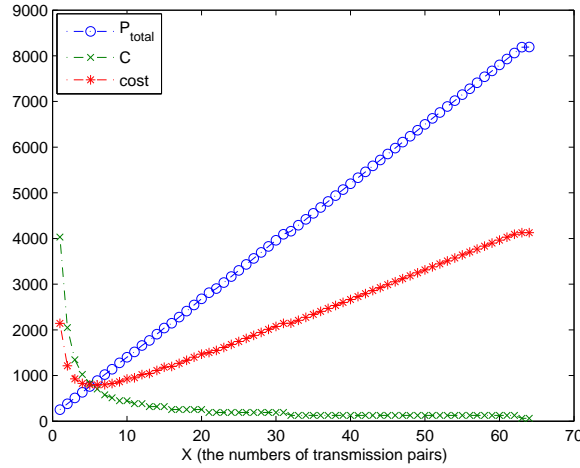Figure 5.10: Performance Comparison: Control Packet Overhead vs Data Rate

Figure 5.11: The Cost Function (Numbers of Nodes = 64)

where S^2 means the simulation area 400×400, and the d^2 means the transmission area $(200)^2$.

The probability of collision is 0.242, 0.448, 0.609, 0.729, and 0.815 when number of neighbor nodes is 5, 10, 15, 20, and 25. So the ATIM window of one ABI is 0.0018, 0.0026, 0.0035, 0.0044, and 0.0051; the duration of one ABI is 0.0116, 0.0134, 0.0163, 0.0203, and 0.0248. According to the cost function as shown in Fig. 5.11, we decide the duration of BI is four ABIs ($X = 4$). The T_{BI}= 0.0464, 0.0536, 0.0652, 0.0812, and 0.0992, respectively. The T_{AW}= 0.0072, 0.0104, 0.014, 0.0176, and 0.00204, respectively.

The simulation results between the IRouter scheme with adaptive beacon interval and the IRouter scheme without adaptive beacon interval are shown from Fig. 5.12 to 5.15 :

In Fig. 5.12, the IRouter scheme with adaptive beacon interval saves more energy than the IRouter scheme without adaptive beacon interval. The IRouter scheme with adaptive beacon interval improves the end-to-end delay as shown in Fig. 5.14. The delivery ratio and the numbers of control packets are very close in Fig. 5.13 and 5.15.

The plots in Figs. 5.16, 5.18, 5.20, and 5.22 show the performance comparison between these three protocols under different numbers of the MNs within the simulation topology (i.e. numbers of the MNs equal to 24, 44, 64, 84, and 104; V = 10 m/sec); while the plots in Figs. 5.17, 5.19, 5.21, and 5.23 illustrate the comparison with different MN's velocity (i.e. V = 5,
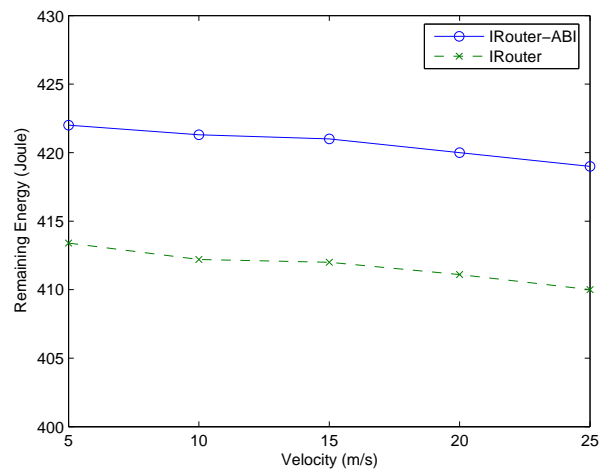
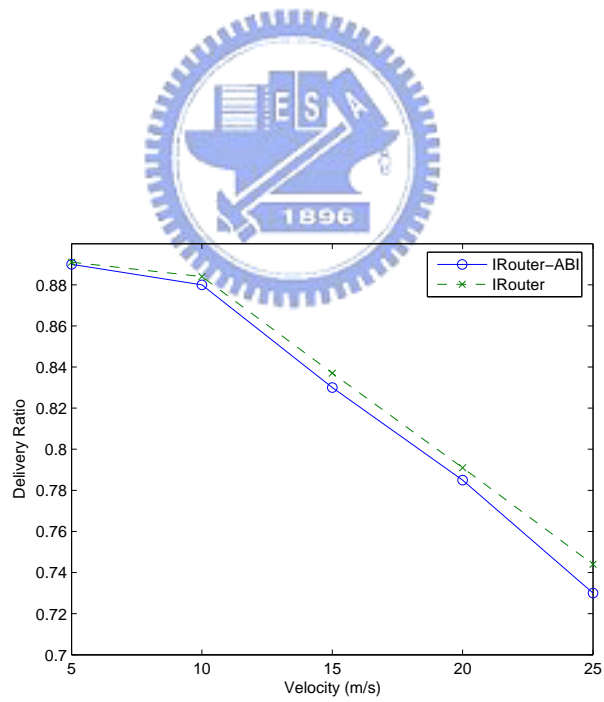Figure 5.12: Performance Comparison: Remaining Energy vs Velocity (Numbers of Nodes = 64)

Figure 5.13: Performance Comparison: Packet Delivery Ratio vs Velocity (Numbers of Nodes = 64)
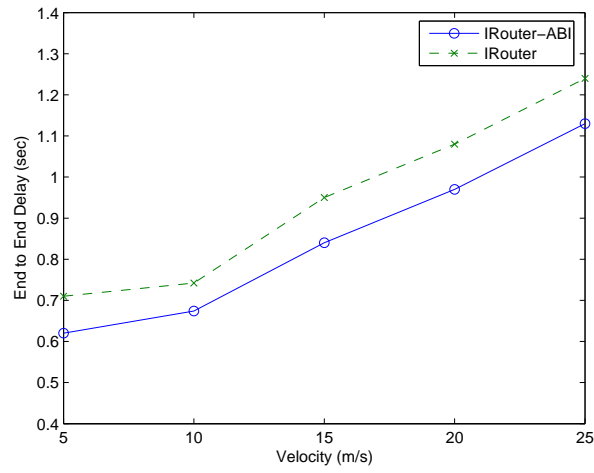
Figure 5.14: Performance Comparison: End-to-End Delay vs Velocity (Numbers of Nodes = 64)
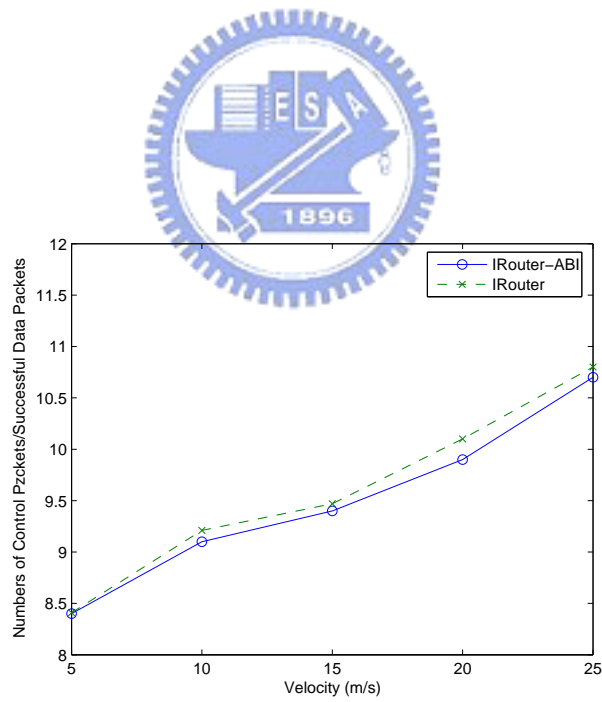

Figure 5.15: Performance Comparison: Control Packet Overhead vs Velocity (Numbers of Nodes = 64)
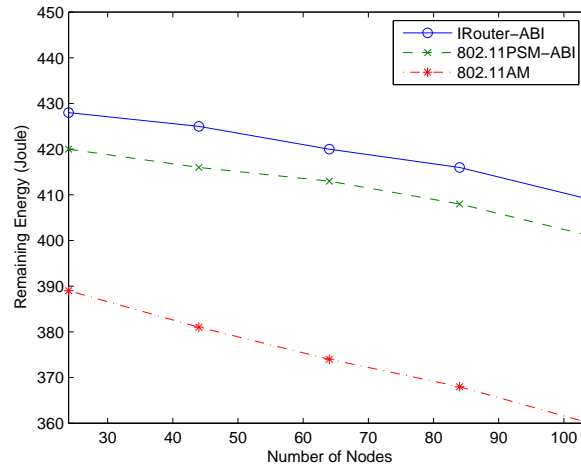
Figure 5.16: Performance Comparison: Remaining Energy vs Number of Nodes (Velocity = 10 m/s)

10, 15, 20, and 25 m/sec; numbers of the MNs = 64).

As can be seen from Fig. 5.16 and 5.17 for the average remaining energy of the MNs, the proposed IRouter scheme can achieve better energy conservation comparing with the other two algorithms. In most cases, The IRouter scheme preserves around 40 joule of the remaining power more than that from the 802.11 AM. The routing efficiency obtained from the IRouter scheme can be observed from Figs. 5.18, 5.19, 5.20,and 5.21. Comparing with the 802.11 AM, Only around 3% decreases on the packet delivery ratio is observed by using the proposed IRouter scheme (as shown in the plot of Fig. 5.19 under V = 25 m/sec). Improvement for the end-to-end delay of packet delivery is also obtained by the IRouter algorithm, which is around 1.0 sec less comparing with the IEEE 802.11 PSM (as shown in the right plot of Fig. 5.21 under V = 25 m/sec). It can be observed from Fig. 5.22, and 5.23 that the control packet overhead of the IRouter is comparably less than that from the 802.11 PSM. The merits of using the IRouter scheme can be seen from these simulation results. The proposed IRouter algorithm offers better energy conservation and routing efficiency within the ad hoc environment.
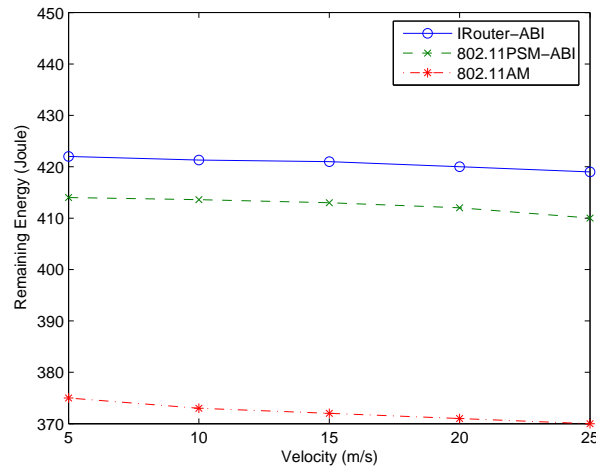
Figure 5.17: Performance Comparison: Remaining Energy vs Velocity (Numbers of Nodes = 64)
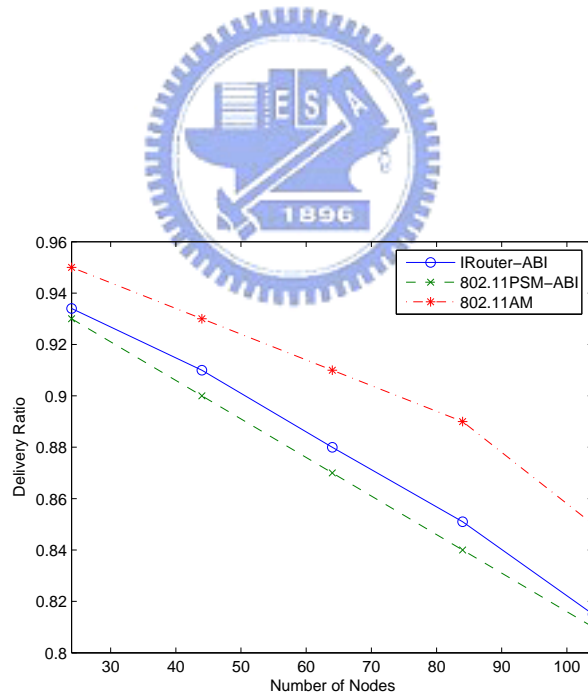

Figure 5.18: Performance Comparison: Packet Delivery Ratio vs Number of Nodes (Velocity = 10 m/s)
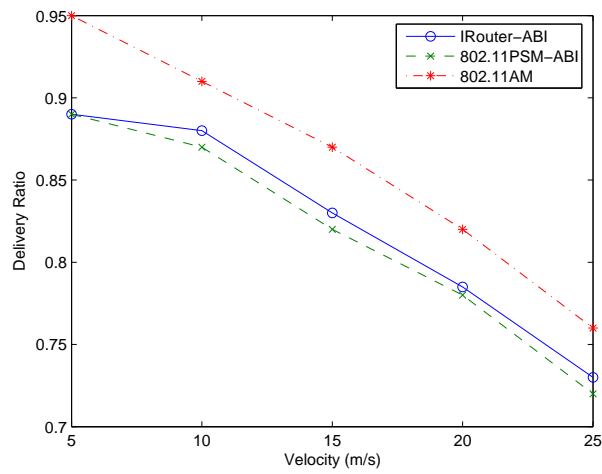
Figure 5.19: Performance Comparison: Packet Delivery Ratio vs Velocity (Numbers of Nodes = 64)
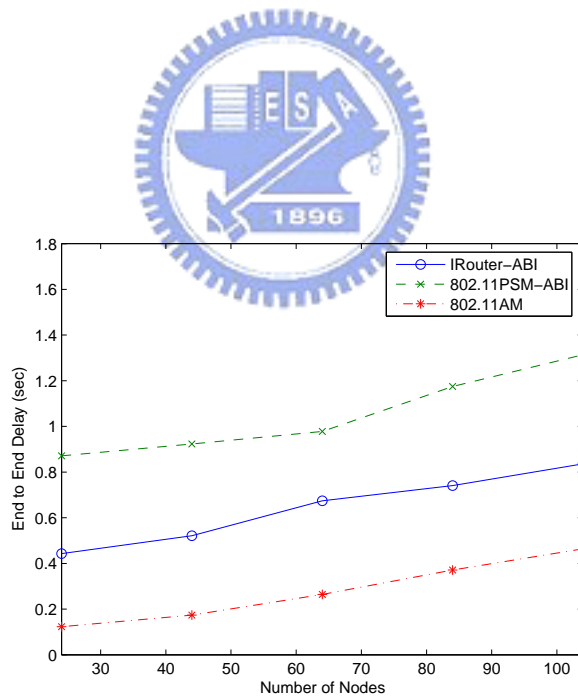

Figure 5.20: Performance Comparison: End-to-End Delay vs Number of Nodes (Velocity = 10 m/s)
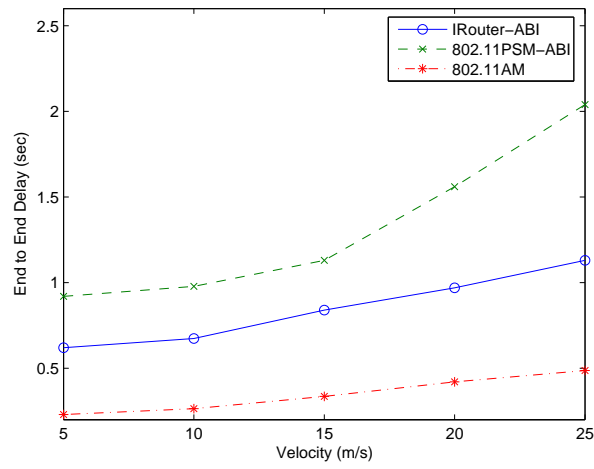
59

Figure 5.21: Performance Comparison: End-to-End Delay vs Velocity (Numbers of Nodes = 64)
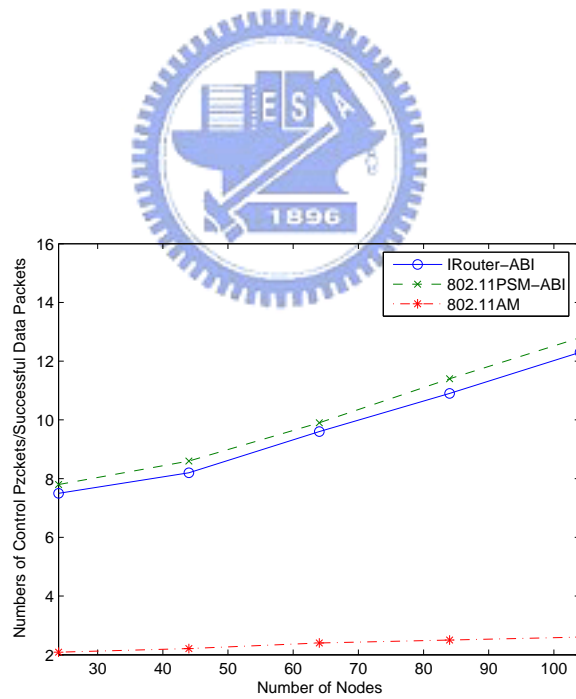

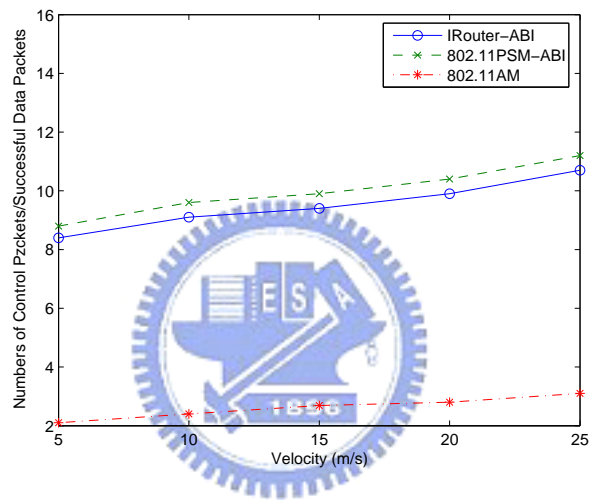Figure 5.22: Performance Comparison: Control Packet Overhead vs Number of Nodes (Velocity = 10 m/s)

60

Figure 5.23: Performance Comparison: Control Packet Overhead vs Velocity (Numbers of Nodes = 64)

Chapter 6

Conclusion

An Intelligent Router-Assisted (IRouter) power-saving Medium Access Control protocol and the adaptive beacon interval are proposed in this thesis. The IRouter scheme incorporates partial routing information within the MAC layer for each mobile node. The packet delivery between several mobile nodes can be achieved within the same beacon interval. The duration of the adaptive beacon interval is calculated to conserve energy; while the duration of beacon interval is shorter, the power consumption is reduced, but the numbers of control packets are increased. According to different load of network density, the duration of the adaptive interval is also different. We can decide how many transmission pairs are potentially to be transmitted in one beacon interval by the defined cost function. The merits of the proposed IRouter scheme are evaluated via simulations. The IRouter scheme with adaptive beacon interval can save more energy as shown in simulation results. Both the routing efficiency and the power conservation can be preserved by adopting the IRouter scheme in the MAC protocol design.

Bibliography

[1] L. M. Feeny and M. Nilsson, "Investigating the Energy Consumption of a Wireless Network Interface in an Ad Hoc Networking Environment," *Proceedings of IEEE INFOCOM*, Vol. 3, April 2001, pp. 1548-1557.

[2] IEEE Computer Society, "IEEE Standard 802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *The Institute of Electrical and Electronics Engineers*, New York, N.Y., 1997.

[3] H. Woesner, J.-P. Ebert, M. Schläger, and A. Wolisz, "Power-saving Mechanisms in Emerging Standards for Wireless LANs: The MAC Level Perspective," *IEEE Personal Communications*, Vol. 5, No. 3, June 1998, pp. 40-48.

[4] C. Rohl, H. Woesner, and A. Wolisz, "A Short Look on Power Saving Mechanism in the Wireless LAN Standard Draft IEEE 802.11," *Proceedings of the 6th WINLAB Workshop on Third Generation Wireless Systems*, New Brunswick, N.J., March 1997.

[5] E.-S Jung and N. H. Vaidya, "Improving IEEE 802.11 Power Saving Mechanism," *Technical Report*, July 7, 2004.

[6] L. Bononi, M. Conti, and L. Donatiello, "A Distributed Mechanism for Power Saving in IEEE 802.11 Wireless LANs," *ACM/Kluwer Mobile Networks and Applications (MONET)*, 2001, pp. 211-222.

[7] C. S. Raghavendra and S. Singh, "PAMAS - Power-Aware Multi-Access Protocol with Signaling for Ad Hoc Networks," *ACM Computer Communication Review*, 1998.

[8] C.-K. Toh, "Maximum Battery Life Routing to Support Ubiquitous Mobile Computing in Wireless Ad Hoc Networks," *IEEE Communications Magazine*, Vol. 39, Issue 6, June 2001, pp. 138-147.

[9] J. Gomez, A.-T. Campbell, M. Naghshineh, and C. Bisdikian. "Conserving transmission power in wireless ad hoc networks." *Proceedings of the Ninth International Conference on Network Protocols (ICNP 2001),* November 2001, pp. 24-34.

[10] C.-K. Toh, Hiroshi Cobb, and David A. Scott. "Performance evaluation of battery-life-aware routing schemes for wireless ad hoc networks." *Proceedings of IEEE International Conference on ommunications 2001 (ICC 2001),* volume 9, June 2001, , pp. 2824-2829.

[11] K. Tsudaka, M. Kawahara, A. Matsumoto, and H. Okada. "Power control routing for multi hop wireless ad-hoc network." *Proceedings of IEEE Global Telecommunications Conference 2001 (GLOBECOM 01),* volume 5, October 2001, pp. 2819-2824.

[12] R. Zheng and R. Kravets, "On-demand Power Management for Ad Hoc Networks," *Proceedings of IEEE INFOCOM,* March 2003, pp. 481-491.

[13] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris. "Span: An energy-efficient co-ordination algorithm for topology maintenance in ad hoc wireless networks." *Proceedings of the Seventh Annual International Conference on Mobile Computing and Networking (MobiCom01),* July 2001, pp. 85-96.

[14] J.-H. Ryu, S. Song, and D.-H. Cho, "Clustering scheme for energy conservation in two-tiered mobile ad hoc networks." *Electronics Letters,* , May 2001, pp. 710-711.

[15] L. Bononi, M. Conti, and L. Donatiello. "A distributed contention control mechanism for power saving in random-access ad-hoc wireless local area networks." *Proceedings of 1999 IEEE International Workshop on Mobile Multimedia Communications (MoMuC99),* November 1999, pp. 114-123.

[16] Y. Fang and A.-B. McDonald. "Cross-layer performance effects of path coupling in wireless ad hoc networks: Power and throughput implications of ieee 802.11 mac." *Proceeding*

of 21st IEEE International Performance, Computing, and Communication Conference (IPCCC 2002), February 2002, pp. 281-290.

[17] J.-C. Chen, K. M. Sivalingam, P. Agrawal, and S. Kishore. "A comparison of mac protocols for wireless local networks based on battery power consumption." *Proceedings of the 17th Annual Joint Conference of the IEEE Computer and Communications Societies 1998 (INFOCOM 98),* volume 1, April 1998, pp. 150-157.

[18] Y.-C. Tseng, C.-S. Hsu, and T.-Y. Hsieh. "Powersaving protocols for ieee 802.11-based multi-hop ad hoc network." *Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies 2002 (INFOCOM 2002),* volume 1, June 2002, pp. 200-209.

[19] W. Ye, J. Heideman, and D. Estrin. "An energy-efficient mac protocol for wireless sensor networks." *Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies 2002 (INFOCOM 2002),* volume 1, June 2002, pp. 200-209.

[20] Y.-C. Tseng, C.-S. Hsu, and T.-Y. Hsieh, "Power-Saving Protocols for IEEE 802.11-Based Multi-Hop Ad Hoc Networks," *IEEE INFOCOM* , 2002.

[21] E.-S. Jung and N. H. Vaidya, "A Power Control MAC Protocol for Ad Hoc Networks," *Proceedings of the 8th Annual International Conference on Mobile Computing and Networking*, Atlanta, Georgia, Sept. 2002, pp. 36-47.

[22] J. P. Monks, V. Bharghavan, and W. mei W. Hwu., "A power controlled multiple access protocol for wireless packet networks," *Proceedings of the 20th Annual Joint Conference of the IEEE Computer and Communications Societies 2001 (INFOCOM 01)*, April 2001, pp. 219-228.

[23] J. Zhang, Z. Fang, and B. Bensaou, "Adaptive Power control Algorithm for Ad Hoc NetworksWith Short and Long Term Packet Correlations," *The IEEE Conference Digital Object Identifier 10.1109* , November 2005, pp. 276-283.

[24] S.-L. Wu, P.-C. Tseng, "An energy efficient MAC protocol for IEEE 802.11 WLANs," *Proceedings. Second Annual Conference*, Communication Networks and Services Research, May 2004, pp. 137-145.

[25] Y. Wang, "MEDIUM ACCESS CONTROL IN AD HOC NETWORKS WITH OMNI-DIRECTIONAL AND DIRECTIONAL ANTENNAS," *A dissertation submitted in partial satisfaction of the requirements for the degree of DOCTOR OF PHILOSOPHY in COMPUTER ENGINEERING*, June 2004

[26] J. Heidemann, N. Bulusu, J. Elson, C. Intanagonwiwak, K. Lan, Y. Xu, W. Ye, D. Estrin, and R. Govindan, "Effects of Detail in Wireless Network Simulation," *Proceedings of the SCS Multiconference on Distributed Simulation*, January 2001, pp. 3-11.

[27] C. E. Perkins, and P. Bhagwat, "Highly Dynamic Destination Sequence Distance Vector (DSDV) Routing for Mobile Computers," *Proceedings of the ACM SIGCOMM '94 Conference*, August 1994, pp.234-244.

[28] S. Murthy and J. J. Garcia-Luna-Aceves, "An Efficient Routing Protocol for Wireless Networks," *ACM Mobile Networks Appl. J., Special Issue on Routing in Mobile Communication Networks,* October 1996, pp. 183-197.

[29] C. Perkins and E. Royer, "Ad-hoc On-demand Distance Vector Routing," *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, February 1999, pp.90-100.

[30] D. B. Johnson, D. A. Maltz, and J. Broch, "DSR: The Dynamic Source Routing Protocol for Multi-Hop Wireless Ad Hoc Networks," *Ad Hoc Networking, edited by C. E. Perkins, Addison-Wesley,* 2001.

[31] V. D. Park and M. S. Corson, "A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks," *Proceedings of IEEE Infocom '97*, April 1997, pp. 1405-1413.

[32] C.-K. Toh, "A novel Distributed Routing Protocol to Support Ad-hoc Mobile Computing", *Proceedings of 15th IEEE Annual International Phoenix Conference on Computers and Communications,* March 1996, pp. 480-486.

[33] R. Dube, C. D. Rais, K.-Y. Wang, and S. K. Tripathi, "Signal Stability Based Adaptive Routing (SSA) for Ad-hoc Mobile Networks," *IEEE Personal Communications,* February 1997, pp. 36-45.