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Power Efficient Mobile Ad-hoc Network

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement of the degree of
Doctor of Philosophy

by

Mr. Ye Ming Hua

School of Computer Engineering

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Abstract

A MANET is a self-configuring and self-organizing network of mobile hosts connected by wireless links. It is an autonomous system that each mobile host operates not only as an end-system, but also as a router to forward packets. They are free to move randomly and organize themselves arbitrarily. Consequently, the network topology may change rapidly and unpredictably. Such a network may operate in a standalone fashion, or may be connected to the larger Internet. MANET has attracted a lot of research interests recently due to its flexibility and availability in providing reliable wireless communication to mobile devices with no predefined infrastructure. MANET operates in a homogenous and distributed manner and communication is mainly peer-to-peer based. Therefore, the existing standardized communication protocols for Internet can not be directly employed to MANET scenario or the performance degradation is unacceptable. Furthermore, mobile devices are often powered by rechargeable batteries, which can only provide a finite amount of energy due to the constraint of weight and capacity. With the increasing demand for computational power and high speed wireless communication that are power consuming, energy efficiency is considered as one of the most important protocol design issues in the research area of MANET, which has not been addressed in the wired network context before.

The popular IEEE 802.11 MAC/PHY layer wireless protocol [1], as the de facto standard for Wireless Local Area Network (LAN), also incorporates an ad-hoc networking system when no wireless access points are present. Furthermore, IEEE 802.11 MAC/PHY layer protocol are widely used in MANET research area as the cornerstone and many higher-level protocols have been proposed to aggregate various IEEE 802.11 ad-hoc networks into MANETs. Power efficiency is also addressed in IEEE 802.11 protocol as an essential consideration and protocol component. In this thesis, we focus on different perspectives of IEEE 802.11 MAC protocol aiming at improving the power efficiency of the protocol and performance.

IEEE 802.11 standard specified a Power Saving (PS) mechanism for mobile stations within an Independent Basic Service Set (IBSS). TSF is utilized to keep the timers of all mobile stations in the same IBSS synchronized. Transmission time is therefore divided in to a series of Beacon Interval (BI) with TSF beacon transmission at the beginning of each BI. Mobile stations announce their pending data packets within Announcement Traffic Indication Message (ATIM) Window immediately followed by the beacon. After the ATIM window, the announced data packets are transmitted using contention-based DCF access procedure. We propose a modified mechanism by sending the TSF beacon at the end of each ATIM window by the station that successfully transmitted the first ATIM announcement during current BI. Upon actively overhearing the traffic announcements within ATIM window, the packet transmission can be properly scheduled by piggyback transmission arrangement information within the beacon. Several scheduling mechanisms are proposed that will provide a fair and power efficient service for all mobile stations. The scheduling information will ensure the data packets transmission to be contention-free and minimize the total time that mobile stations have to stay in the active state. The complexity and performance of the proposed algorithms are analyzed using simulation method. The results show that the proposed algorithms performance better in reducing the total active time of all mobile stations compared with original IEEE 802.11 protocol.

Based on the observation that power saving mechanism of IEEE 802.11 depends much on reliable time synchronization, we present a modification to the existing TSF for DCF by using differentiated backoff counter range according to the clock accuracy of the stations. Using the proposed method, the probability of collision among beacons can be significantly reduced. This makes the proposed mechanism more scalable for large network, in which large number of stations are competing with each other for access to the shared wireless channel. Furthermore, less time is required for the successful transmission of the beacon frames as a result of the collision resolution, which is equivalent to less energy consumption and high bandwidth utilization. In addition, the clocks can be converged quickly and a smaller clock deviation can be achieved compared with previous approaches.

Furthermore, we incorporate the runtime battery simulation model into the energy model of NS-2 simulator. Based on the modeling of battery recovery effect, we proposed a scheme that actively defers the data packet transmission to take advantage of the battery recovery effect. Based on the proposed enhancement to IEEE 802.11 that efficiently exploits the battery

capacity, significant improvement of the battery lifetime can be achieved with the trade-off of only the minimum additional packet delay. Our proposed power efficient protocol, which can be easily incorporated to the existing power saving mode of IEEE 802.11, is ideally suitable for applications, such as web browsing and email which are not time-critical tasks.

Infrastructure based wireless LAN technology has also been widely used in today's personal communication environment. We propose a hybrid protocol which intelligently chooses the Access Point (AP) assisted DCF and enhanced PCF transmission mechanism of IEEE 802.11 protocol in an infrastructure based wireless LAN environment. We use Received Signal Strength Indicator (RSSI) method to estimate the distance between mobile stations and AP. Based on the estimation, mobile stations can efficiently communicate directly instead of being routed by access point if they are in the vicinity of each other. We also further extend this protocol by utilizing the historical end-to-end delay information to decide the waking up time of mobile stations. The throughput is increased significantly due to the reduction of channel utilization through the direct transmission and waking up time estimation. The proposed protocol is a hybrid of AP assisted DCF and PCF operation, which is more flexible and fault-tolerant, and can be readily reverted to the traditional IEEE 802.11 protocol for compatible reason when required.

Selected Publications

- Journal Publications

- Ye Ming Hua, Lau Chiew Tong, and Benjamin Premkumar, A Power-Efficient Access Point Operation for Infrastructure Basic Service Set in IEEE 802.11 MAC Protocol, EURASIP Journal on Wireless Communications and Networking, vol. 2006, Article ID 63728, 14 pages, 2006. doi:10.1155/WCN/2006/63728
- M. H. Ye, C. T. Lau and A. B. Premkumar, "Traffic Scheduling mechanism Based on Graph Theory for Power Saving Mode of IEEE 802.11 Distributed Coordinator Function", to appear in International Journal of Ad Hoc and Ubiquitous Computing, 2007.
- M. H. Ye, C. T. Lau and A. B. Premkumar, "Modified Power Saving Mode in IEEE 802.11 Distributed Coordinator Function", in *Performance issues of Wireless LANs, PANs and ad hoc networks*, Elsevier Computer Communications, Volume 28, Issue 10, Pages 1214-1224, June 2005.
- M. H. Ye, C. T. Lau and A. B. Premkumar, "Scheduling Mechanism for the Modified Power Saving Mode in IEEE 802.11 Distributed Coordinator Function", in *WSEAS TRANSACTIONS on COMMUNICATIONS*, Page 617-625, Issue 4, Volume 5, April 2006.
- M. H. Ye, C. T. Lau and A. B. Premkumar, "Power Efficient MAC Protocol Through Intelligent Transmission Mechanism Selection for IEEE 802.11 Based Infrastructure Basic Service Set", in *WSEAS TRANSACTIONS on COMMUNICATIONS*, Page 922-930, Issue 5, Volume 5, May 2006.

- Conference Publications

- M. H. Ye, C. T. Lau and A. B. Premkumar, "Enhancing the power saving mode in IEEE 802.11 Distributor Coordinator Function using Traffic Scheduling", in *8th WSEAS International Conference on AUTOMATIC CONTROL, MODELLING and SIMULATION (ACMOS'06)*, Prague, Czech Republic, March 12-14, 2006.

- M. H. Ye, C. T. Lau and A. B. Premkumar, "Enhanced Point Coordinator Function in IEEE 802.11 MAC Protocol for Infrastructure Basic Service Set", in *5th WSEAS International Conference on APPLIED COMPUTER SCIENCE (ACOS '06)*, Hang Zhou, China, April 16-18, 2006.
- M. H. Ye, C. T. Lau and A. B. Premkumar, "Modified Time Synchronization Function in IEEE 802.11 Using Differentiated Contention Window", in *the Fourth IEEE International Conference on Information, Communications & Signal Processing and Fourth Pacific-Rim Conference on Multimedia (ICICS-PCM 2003)*, December 2003, Singapore.
- M. H. Ye, C. T. Lau and A. B. Premkumar, "Enhanced IEEE 802.11 Power Saving mode using Battery Recovery Effect", in *the 7th IEEE International Symposium on Consumer Electronics 2003*, December 2003, Sydney, Australia.

List of Acronyms

MANET	Mobile Ad Hoc Network
GSM	Global System for Mobile communication
LAN	Local Area Network
IR	Infrared
CSMA	Carrier Sensing Multiple Access
CA	Collision Avoidance
SNR	Signal to Noise Ratio
IBSS	Independent Basic Service Set
TSF	Time Synchronization Function
BI	Beacon Interval
ATIM	Announcement Traffic Indication Message
DCF	Distributed Coordination Function
PCF	Point Coordinator Function
RSSI	Received Signal Strength Indicator
ISP	Internet Service Provider
OSI	Open Systems Interconnection
MAC	Medium Access Control
AP	Access Point
RF	Radio Frequency
TPC	Transmission Power Control

BER	Bit Error Rate
QOS	Quality of Service
CDMA	Code Division Multiple Access
PDU	Protocol Data Unit
FEC	Forward Error Correcting
CRC	Cyclic Redundancy Check
TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access
BTMA	Busy Tone Multiple Access
RI-BTMA	Receiver Initiated - Busy Tone Multiple Access
MACA	Multiple Access with Collision Avoidance
RTS	Request to Send
CTS	Clear to Send
PCM	Power Control MAC
PCMA	Power Controlled Multiple Access
SIFS	Short Inter Frame Space
DIFS	Distributed Inter Frame Space
PIFS	Point Coordination Inter Frame Space
AIFS	Access Category Inter Frame Space
PAMAS	Power Aware Multi Access
EY-NPMA	Elimination Yield - Non-Preemptive Priority Multiple Access
NMRL	Normalized MAC PDU Residual Lifetime

CFP	Contention Free Period
CF	Contention Free
EC-MAC	Energy Conserving Medium Access Control
FSM	Frame Synchronization Message
PSM	Power Saving Mode
PEM	Power-Efficient MAC
MIS	Maximum Independent Set
SP-TPC	Self-Protective Transmit Power Control
CCA	Clear Channel Assessment
NAV	Network Allocation Vector
MST	Minimum Spanning Tree
MAHS	Multiple Access Hybrid Scheduling
AC	Access Categories
TXOP	Transmission Opportunity
CW	Contention Windows
RMD	Random Minimal Degree
BSS	Basic Service Set
DLP	Direct Link Protocol
UWB	Ultra Wide Band
TOA	Time of Arrival
TDOA	Time Difference of Arrival
RTT	Round Trip Time

FHSS	Frequency Hopping Spread Spectrum
TBTT	Target Beacon Transmission Time
DSSS	Direct Sequence Spread Spectrum
NTP	Network Time Protocol

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Chapter 1

Introduction

1.1 Background

Computing and communication anytime, any where and to anybody is a global trend in today's technology and economic development. There is an increasing tendency to provide wireless networking facility to every possible type of portable information processing equipment. Connecting these computing devices with each other, sharing the information and computational power such as data files, disk storage space and CPU processing power is becoming a fundamental and natural requirement for the efficient and convenient usage of computer resources. This drives the demand and necessity for these computers to form a temporary network in the environment where there is no pre-built network infrastructure. MANET [2] therefore came into picture, denoted as an autonomous system of mobile routers (and associated hosts) connected by wireless communication links and the union of which forms a random and multi-hop graph. Such network is rapidly deployable through self governing, easily reconfigurable without intervention and totally independent of any centralized infrastructure support.

Prominent examples of how large networks can be constructed of fixed nodes include the telephone system and the Internet. The Global System for Mobile communication (GSM) [3] network shows how these wired networks can be extended to include large numbers of mobile nodes. However, a fixed infrastructure is required which involves large amount of investment before such networks are useful, such as central offices, trunks, local loops in the telephone

system and base station system for the cellular network. Furthermore, maintaining and upgrade the fixed infrastructure system has proven expensive and difficult. There are many situations that Ad Hoc networks are desirable. There are situations where that users in a specific may be so sparse or dense that the appropriate level of fixed infrastructure is not an economical investment. There are also scenarios that the fixed infrastructure exists but cannot be relied upon, such as during disaster recovery. Mobile ad hoc networks are attracting a lot of attention these days due to their self-configuring and self-organizing characteristics, which little efforts are needed to deploy the network. The mobile Ad Hoc networks can be an economical and effective communication option in the remote area. It can also be a substitution for local area networks, since zero configuration requirement is also an attractive point which makes it suitable for home networks or for users who either don't know how to configure a network or don't have an inclination to do so.

In the MANET context, existing methods or protocols that work well in wired network are often not able to provide data services in real time with high throughput, low delay and fault tolerance which are desired by users and applications. It is worth noting that MANET has the following characteristics, which render most well-defined Internet protocols inappropriate for the MANET scenarios and pose significant design challenges in different perspectives.

- Multi-hop nature.

Mobile nodes communicate with each other through the wireless network interface. The transmission medium can be either an 802.11 Infrared (IR) Physical Layer interface [4] (with a limited transmission range within 1-3 meters), or wireless radio as in the case of IEEE 802.11 based wireless LAN technology (using 2.4GHz and 5GHz wireless radio with transmission range typically not more than 300 meters [5]) and Bluetooth [6] (maximum 100 meters coverage range, normally 10-20 meters). Given the limited coverage range of the wireless transceiver, in order to communicate with the mobile nodes out of

direct transmission, each intermediate node has to act as router to forward the traffic to the remote destination. A multi-hop routing protocol has to be defined to form a cooperative environment that makes communication possible in a more scalable manner. It is completely different from the infrastructure network or the cellular network concept, wherein communication is organized and routed through the centralized authority - the base station system.

Figure 1.1: Multi-hop Radio Communication

- Dynamic topology.

Because of the mobility of nodes, the network topologies change from time to time dynamically with unpredictable patterns. There can be new mobile nodes joining and leaving the network any time. The direct wireless connection between two nodes can be invalid if they move in opposite direction and out of transmission range of each other. Two separated nodes can have a direct connection if they move close in vicinity of the radio coverage. This is the major challenge for the routing protocols that require a mechanism to discover and maintain a reliable multi-hop routes in such a changing network [7].

- Bandwidth-constraint, variable capacity links.

MANET is based on wireless links, which have significant lower capacity than their hardwired counterpart. Furthermore, Carrier Sensing Multiple Access (CSMA)/Collision Avoidance (CA) based multiple access techniques are widely used to increase the radio channel utilization and support more subscribers on a single wireless channel to lower the

overall cost. This often leads to an even lower channel capacity per user because of the back-off and collisions introduced by using the contention based channel access procedures [8, 9, 10]. The wireless communication protocol should minimize the protocol overhead and maintain end-to-end quality of service requirements.

- Unreliable wireless connection with high Signal to Noise Ratio (SNR) and transmission error rate.

Signal quality between a wireless transmission source and a receiver, usually measured as a signal-to-noise ratio, is difficult to model and quantify. The complex mechanism of electromagnetic wave propagation can be attributed to reflection, diffraction, and scattering effects [11]. Many mobile radio systems will operate in urban areas or within buildings where time varying signal fading and shadowing effects may naturally occur. Such effects make signal strength prediction and short-term estimation of link quality more complex.

- Power-constraint operation.

Mobile devices are often powered by batteries with limited capacity [12]. The MAC and routing protocol design can dramatically affect the battery life time of wireless communication devices [13, 14]. Unless there is a significant break through in battery technology, the most import system design criteria for optimization may be that of power conservation.

With the increasing popularity of portable devices as well as progress in wireless communication technology, Ad Hoc networking is gaining importance with the increasing number of widespread applications. Compared with the infrastructure based network like the cellular network, the infrastructure back bone composed of the base station system has to be setup in advance, and mobiles cannot communicate with each other out of the coverage of the base station, even they are in close vicinity and within direct radio coverage. However, MANET can be applied to the place where there is little or no communication infrastructure or the existing

infrastructure is expensive or inconvenient to use. Furthermore, MANET allows the devices to maintain connections to the network as well as easily adding and removing devices to and from the network. The set of applications for MANETs is diverse, ranging from large-scale, mobile, highly dynamic networks, to small, static networks that are constrained by power sources. Besides the legacy applications that move from traditional infrastructure environment into the ad hoc context, a great deal of new services can and will be generated for the new environment. MANET can easily operate as robust, inexpensive alternatives or enhancement to the infrastructure network. Particularly in the military operation and disaster relief scenarios, in which a fast-deployable and reliable communication mechanism is often preferred. In addition, the ability of communication anytime and anywhere through cooperative mobile data exchange can provide large variety of applications for MANET technology. Typical applications include office environment, Internet Service Provider (ISP) last mile access and resources sharing or multi-point video and audio conference in a meeting room or large lecture hall, even playing game with the collaboration of a group of people together, etc. The massive wireless hot spot nowadays also provide the opportunity for millions of people traveling each year to access e-mail, surf the Web, and interface with corporate applications.

1.2 Motivation and Objectives

Wireless portable devices are expected to have a prosperously development in the near future to provide the facilities that can realize a pervasive computation and communication prospect to our daily life. The future applications of such mobile devices require highly reliable wireless communication capability with considerable long communication range and sufficient bandwidth to support the increasing demand of exchanging more and more multimedia resources. IEEE 802.11 based wireless LAN technology, which satisfies nowadays communication requirements, is gaining its important role in the development of wireless network and attracts a lot of research interests. Furthermore, most of the research on MANET assumes IEEE 802.11 wireless LAN

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protocol as the PHY/MAC layer specification since it is a well-developed and widely used model, which has already been commercialized and accepted as the de facto standard in market. In order to build a power efficient MANET using available technology, the power efficiency of IEEE 802.11 PHY/MAC standard is the first or perhaps one of the most important issues to be considered.

Today, the commonly used IEEE 802.11 based wireless LAN devices available in market can provide a bandwidth of 11Mbps (IEEE 802.11b at 2.4 GHz) 54Mbps (IEEE 802.11a at 5GHz and 802.11g at 2.4 GHz) with 100 meters to 250 meters transmission range. Although there is still a significant gap as compared with the high speed wired LAN counterpart, IEEE 802.11 performs much better than other existing wireless standards, such as Bluetooth and Infrared. For short range and low power wireless (less than 10 meters) communications among personal devices such as PDA, Bluetooth and subsequent IEEE standards (802.15) [15] are taking effects. For long range wireless communications in the metropolitan areas, WiMax as defined in the IEEE 802.16 [16] is the standard in the future. So IEEE 802.11 based wireless LAN is uniquely suitable and versatile for today's communication requirements of the portable devices with the best performance and cost tradeoff.

Figure 1.2: Energy consumption investigation of wireless network interface card

IEEE 802.11 based wireless LAN devices are often powered by batteries or depletable source of energy to achieve mobility and flexibility. Due to great constrain of weight and volume,

batteries can provide only a finite amount of energy. However, transmitting and receiving data through the wireless radio transceiver is very costly in the perspective of energy consumption, especially when a random-access wireless radio channel is share among many users [17, 18, 19]. With the increase of transmission range and high speed transmission capability, as shown in Figure 1.2, IEEE 802.11 base wireless LAN leads to a high energy consumption which may contribute to almost 25% of the total energy consumption of a laptop computer equipped with wireless network interface card [20, 21]. However, as far as handheld devices are concerned, this portion is even more significant [22], because typically handheld devices are not equipped with hard disk and the size of TFT display screen is much smaller than that in laptop computers [23], which are the major energy consumption beside the network interface. Unless there is a break through in the battery technology, research on the power efficient method for IEEE 802.11 based wireless LAN is always worth-well.

Figure 1.3: MAC protocol within a simplified network protocol stack

Many benefits can be gained from the process of breaking up the functions or tasks of networking into smaller sub-layers, and defining standard interfaces between these layers. The layers break a large, complex set of concepts and protocols into smaller pieces, making it easier to understand, to implement with hardware and software, and to troubleshoot. This also provides a conceptual basis for understanding how a complex set of protocols can work

together with the hardware to build up a powerful and complicated communication system. The layered approaches reduce the complexity of development which allows easier program changes and faster product evolution. It also improves the inter-operability, so that products from multiple vendors developed to meet the same networking standards can work seamlessly in the same network. Providing the well defined boundaries and interface between layers, software and hardware can be developed independently and simultaneously and changes in one layer will not propagate to other layers. The traditional Open Systems Interconnection (OSI) [24] protocol stack, as depicted in Figure 1.3, can also be applied to describe the generic wireless communication system. The upper layers of the OSI reference model (application, presentation, and session Layers 7, 6, and 5) define functions focused on the application. The lower four layers (transport, network, data link, and physical Layers 4, 3, 2, and 1) define functions focused on end-to-end delivery of the data. The inherent difficulties of transmitting data over the unreliable wireless channel and issues related to mobility and topology change challenge the design of the protocol stack adopted for wireless networks. In addition, development of protocols for wireless networking should consider energy efficiency as an important design issue in each specific network protocol layer.

The IEEE 802.11 standard is a specification of the physical layer and MAC layer. The physical layer consists of Radio Frequency (RF) circuits, modulation, and channel coding systems. From an energy efficient perspective, considerable attention has already been given to the design of physical layer by efficiently exploring the battery capacity and using microchips designed for low-power. Furthermore, significant improvements and benefits can be achieved by using directional antennas or smart antennas. Transmission Power Control (TPC) is also a very promising area.

MAC protocol governs the multiple access procedure and coordinating and scheduling of transmissions among competing nodes, which is used by the mobile terminals to share the time/frequency or code space among each other in the same region to utilize the limited resources with maximum efficiency. Collision Detection (CD) as widely used in wired Ethernet

[25] is difficult to implement in wireless networks because it requires simultaneous transmission and reception on the same band. However, when a wireless transceiver is actively transmitting, a large fraction of the signal energy will leak into the receiving path, which is much higher than any received signal on the same frequency. To prevent such interference on a single antenna system, a radio's receiver is often turned off when the transmitter is activated and vice versa, which makes it impossible for collision detection. IEEE 802.11 MAC protocol is a multiple access protocol based on the CSMA/CA mechanism. Contention based exponential backoff mechanism is used to reduce the collision since retransmission is required to recover the collided data packets which is considered as a waste of energy. Since packet retransmission consumes unnecessary power and may often lead to unbounded delay, many researches focus on reducing the collision probability for improving the power efficiency of MAC protocol.

Another research direction of the power efficient MAC protocol is based on switching the operation state of the radio transceiver, which is supported by the physical layer implementation [5]. Radio transceiver of the wireless network interface card can operate in the high energy consumption state (active state) and the power saving state. In the active state, the mobile station is capable of transmitting and receiving data packets. However, due to channel contention and collision avoidance mechanism used in the wireless network, mobile nodes spend considerable amount of time in listening mode in which they continuously monitor the channel to detect channel status and incoming packets. In power saving state, a mobile station consumes very small amount of energy compared to the idle listening state. Radio transceiver can switch between the power saving state and active state with acceptable transition time to conserve energy. The power saving mode specified for the IEEE 802.11 standard fall into this category.

In this thesis, we propose modifications to IEEE 802.11 PS mode to reduce collision probability in the contention period and minimize the time that mobile stations have to stay in active state. Various scheduling mechanisms are proposed and discussed, which can provide a

fair and power efficient service for all mobile stations. The complexity and performance of the proposed algorithms are analyzed using simulation method and analytical models. The results show that the proposed algorithms performance better in reducing the total active time of all mobile stations and improve the network performance compared with original IEEE 802.11 protocol.

Based on the observation that TSF plays an important role the IEEE 802.11 PS mode, we present a modification to the existing TSF for DCF by using different backoff counter range according to the clock accuracy of the stations. Using the proposed method, the probability of collision among beacons can be significantly reduced. This makes the proposed mechanism more scalable for large network. Furthermore, less time is required for the successful transmission of the beacon frames, which result in less energy consumption and high bandwidth utilization. In addition, the clocks can be converged quickly and a smaller clock deviation can be achieved compared with previous approaches. Simulation results show that there are significant improvements.

Furthermore, we incorporate the runtime battery simulation model into the energy model of NS-2 simulator. Based on the modeling of battery recovery effect, we propose a scheme that actively defers the data packet transmission to take advantage of the battery recovery effect. Based on the proposed enhancement to IEEE 802.11 that efficiently exploits the battery capacity, significant improvement of the battery lifetime can be achieved with the trade-off of only the minimum additional packet delay. Our proposed power efficient protocol, which can be easily incorporated to the existing power saving mode of IEEE 802.11, is ideally suitable for applications, such as web browsing and email which are not time-critical tasks.

Infrastructure based wireless LAN technology has also been widely used in today's personal communication environment. We propose a hybrid protocol which intelligently chooses the AP assisted DCF and enhanced PCF transmission mechanism of IEEE 802.11 protocol in an infrastructure based wireless LAN environment. We use RSSI method to estimate the distance

between mobile stations and AP. Based on the estimation, mobile stations can efficiently communicate directly instead of being routed by access point if they are in the vicinity of each other. We also further extend this protocol by utilizing the historical end-to-end delay information to decide on the waking up time of mobile stations. The throughput is increased significantly due to the reduction of channel utilization through the direct transmission and waking up time estimation. The proposed protocol is a hybrid of AP assisted DCF and PCF operation, which is more flexible and fault-tolerant, and can be readily reverted to the traditional IEEE 802.11 protocol for compatible reason when required.

1.3 Thesis Organization

The rest of this thesis is organized as follows. In Chapter 2, we will give an extensive review of the MAC protocol used in MANET with emphasis on energy-efficient enhancements to IEEE 802.11 MAC layer. In Chapter 3, we propose our modification to the power saving mode of IEEE 802.11, which can achieve more energy efficiency and improvement of network performance. In Chapter 4, we enhance the modified power saving mode of IEEE 802.11 protocol by introducing different traffic scheduling mechanisms, which ensure the data packets transmission to be contention-free and minimize the total time that mobile stations have to stay in the active state. The complexity and performance of the proposed algorithms are analyzed using simulation and analytical method. In Chapter 5, we propose a hybrid power efficient protocol, which intelligently chooses the AP assisted DCF and enhanced PCF transmission mechanism of IEEE 802.11 protocol in an infrastructure based wireless LAN environment. In chapter 6, we propose our modification to the time synchronization function of IEEE 802.11 to solve the asynchronism problem and reduce collision among beacons. Sufficient simulation results will also be given to show the significance of our contribution. In chapter 7, we present an enhancement to the existing power saving mode as stipulated in IEEE 802.11 protocol by taking advantage of the battery recovery effect that improves the battery lifetime of portable

CHAPTER 1. INTRODUCTION

devices significantly. Finally, we give the conclusion of this thesis and the outline of our future work in Chapter 8. Clear schedule of the future task and research direction will be addressed, including novel features and possible simulation or emulation methods.

Chapter 2

Literature Review

In this chapter, the background of MANET will be given. A comprehensive overview of the role and details of the protocols that define and control access to the wireless channel, i.e., wireless MAC protocols will be presented. The distinguishing characteristic of wireless communication system and the impact on the design and implementation of MAC protocols will be highlighted first. The power efficient multiple access technique in MANET will be introduced, including the scheduling-based mechanism (centralized, distributed and hybrid) which reduce channel contention and collision probability, the transmission power control schemes which minimize the transmitted power, the dynamic power on/off mechanisms which save energy in listening and overhearing mode, and other techniques such as multiple channels approaches and directional and smart antenna. Literature survey on the PS mode specified for IEEE 802.11 MAC protocol and schemes that improve its power efficiency will also be give in detail.

2.1 Mobile Ad Hoc Network

2.1.1 Novel Feature and Characteristic of MANET

Development of information and communication technology in the future will be mainly based on wireless technology, which provides an ubiquitous and pervasive computing environment to improve the efficiency and convenience of our everyday life. Next generation of mobile communications will include both the well-established infrastructure based wireless networks and

novel infrastructureless MANETs. Traditional second-generation cellular systems and infrastructure based network are still, in some sense, limited by their need for pre-existing and fixed infrastructure (i.e., base stations, switches or routers). For the emerging standard of mobile ad hoc network, this final limitation is eliminated. In MANET scenarios, all the autonomous mobile hosts are operating in a homogenous and distributed manner. Communication is peer-to-peer based without any central control. This provides great potential for users to have many innovative applications. In fact, two or more mobile devices can form an Ad Hoc network when they are close enough to each other [26].

However, in order to achieve a highly dynamic and flexible network, the communication protocol should meet the following constraints and requirements:

- The network topology is highly dynamic due to the mobility of mobile stations that participate to form the ad hoc network [27, 28]. Due to the limited transmission range of wireless transceiver, the random movement of mobile stations often cause frequent wireless communication link breakage and setup, which generally leads to unpredictable change of the topology from time to time [29].
- The wireless communication links between mobile stations are often unstable at higher channel Bit Error Rate (BER), which is subject to noise, fading, and interference [30, 31]. Compared to the wired network, in which there are often dedicated links between adjacent stations, a single end-to-end path can be shared by several sessions in wireless network, which is prone to collision and constrain the available bandwidth. Furthermore, in some scenarios, the path between any pair of mobile stations can traverse multiple wireless links and the link themselves can be heterogeneous [32, 33].
- Physical security is limited due to the wireless transmission, since most of the mobile devices are using omnidirectional antenna [34]. Different Denial-of-service attacks are typically impossible to prevent [35, 36, 37]. Unencrypted data transmission can also be easily overheard within the transmission range [38].

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- In MANET, in order to increase channel utilization rate and lower the cost, the limited radio resources are often shared among many users. This often leads to higher end-to-end delay and jitter as compared with wired network. High level applications (audio, video, etc.) with Quality of Service (QOS) requirement have to be redesigned to operate smoothly in the MANET environment [39].
- In MANET, each mobile terminal is an autonomous node, which may function as both a host and a router. The mobile nodes not only perform the functions as a information processing terminal, but should also be able to perform switching functions as a router, which makes the design of software and hardware more complicated and sophisticated.
- In most cases, the MANET nodes are mobile devices with less CPU processing capability, small memory size, and low power storage. Such devices need optimized algorithms and mechanisms that implement the computing and communicating functions. In addition, mobile stations are often powered by battery or other exhaustible source of energy supply. Consequently, energy efficiency is an important system design issue to enhance the users' experience by prolonging the network and system operation time.

The design and implementation of the MANET requires consideration and collaboration of research on all networking layers, ranging from the physical to the application layer. Despite the fact that the management of the physical layer is of fundamental importance, most of the channel coding, modulation methods, system and antenna design can be directly adopted from the well-developed existing wireless communication technologies, such as cellular network. The most challenging research area that attracts a lot of interests is the MAC layer. MAC protocol governs the procedure that the physical or logical channels (frequency channel, time slot or Code Division Multiple Access (CDMA) code) are shared among many users. Due to the lack of centralized coordinating unit, the fair and efficient access to the medium is dependent on the cooperation of the mobile, which can also have significant impact on the power consumption

Figure 2.1: Applications of mobile ad hoc network

of mobile terminals in MANET. So basically MANET requires a more sophisticated design of MAC layer protocols, which should makes efficient usage of the wireless medium resources and considers the power management of paramount importance.

2.1.2 Provision of the Future Applications

The telecommunication industry is expected to have a significant growth of subscribers for wireless communication services, such as GSM or CDMA cellular communication, Personal Communication System and Mobile IP [40, 41]. Nowadays, information technology is becoming an integrated part of our lives, business and the society. MANET are hereby envisioned to naturally support the requirements for communication anytime, anywhere and to anybody else.

Although MANET is initially stimulated by the demands of applications in military operation, it can also be applied to many commercial scenarios with very good prospect.

- (i) Military operation often takes place in a foreign and hostile territory, where the setup of friendly communication facilities that cover a very large area is unpractical. Wireless communications without any constraint of external infrastructure is often preferred. MANET is inherently suitable in providing such kind of communication services that would allow the military to take advantage of commonplace network technology to maintain an information network between the soldiers, vehicles, and military information head quarters

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as shown in Figure 2.1.a. It is highly reliable and secure, because the low-power radio transceiver have a limited transmission range and technologies such as frequency hopping is often used in military communication, which makes it difficult to be overheard.

- (ii) Sensor network is another example application of the ad hoc wireless network. Sensing devices are designed as a tiny electronic devices equipped with wireless transceiver and different kind of detectors that are capable of collecting information of the surrounding environment, such as temperature, humidity, air quality and noise level, etc. Such information can be used to monitor the environment and predict future changes. Sensors are often deployed to a certain area and the applications require the convergence of data collected by hundreds and thousands of sensors. In order to achieve this, sensors form a multi-hop ad hoc network to exchange, process and aggregate the collected data.
- (iii) MANET can be an alternative communication method when existing network infrastructure is damaged or out-of-service. This is especial very important in the emergency situation, such as natural disaster. A temporary communication network for the rescue teams can be setup quickly and independently or with the aid of the remaining infrastructure. Information is relayed from one rescue team member to others in the vicinity and coordinate the resources and personnel as shown in Figure 2.1.b.
- (iv) Ad hoc networks can autonomously link an instant and temporary multimedia network using notebook computers or PDAs to spread and share information among participants, for example at a conference or classroom. Another appropriate local level application might be in home networks where devices can communicate directly to exchange information. Similarly in other civilian environments like taxicab, sports stadium, boat and small aircraft, MANET communications will have many applications. MANET is naturally suitable for such kind of applications because of its self-governing and autonomous characteristics.

- (v) Short-range MANET can simplify the intercommunication between various mobile devices (such as a PDA, a laptop, and a cellular phone). Tedious wired cables are replaced with wireless connections. Such an ad hoc network can also extend the access to the Internet or other networks by mechanisms e.g. Wireless LAN, GPRS, and UMTS. People can acquire information and communicate with others conveniently as illustrated in Figure 2.1.c. The Personal Area Network (PAN) [15] is potentially a promising application field of MANET in the future pervasive computing context.

2.2 Medium Access Control Protocol in MANET

MAC layer is essential in any kind of the networking protocol [42]. The primary functions of MAC layer are:

- On transmission, assemble data into a MAC Protocol Data Unit (PDU) frame with address and error detection field.
- On reception, disassemble frame, and perform address recognition and error detection.
- Govern access to the transmission medium. All stations should follow the access procedure strictly to get access to the transmission medium fairly and effectively.
- Provide an interface to higher layers and perform flow and error control in order to satisfy the delay bound and QOS requirement.

However due to the unique properties of the wireless transmission medium, error correction and multiple access are the most important issues which make the design of MAC protocols very different from, and more challenging than, wired-line networks.

2.2.1 Error Correction Techniques

The constantly changing of the environment produces important variations in time in the attenuation of the signal. As a consequence of the time-varying channel, errors are more likely

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to occur in wireless transmissions. In IEEE standard for 100BASE-TX fast Ethernet, the BER is typically less than 10^{-10} which results in very low probability of packet error [25]. SNR required for $BER = 10^{-10}$ is 21.8dB. In contrast, wireless channels may have an acceptable BER of 10^{-5} [43], resulting in a much higher probability of packet errors [44]. A BER of 10^{-5} is achieved at a SNR of approximately 1dB. In wired networks, these errors are usually caused by random noise. In contrast, the errors on a wireless link occur in long bursts when the station is in fading or packets collide due to simultaneous transmissions on shared medium. Furthermore, the omnidirectional radio propagation through wireless medium that has no observable boundaries and is vulnerable to various external interference. Packet loss due to errors can be minimized by using one or more of the following three techniques:

- Packet fragmentation. The large packets are divided into smaller fragments and transmitted sequentially. Using smaller packets can reduce the cost of error packets. Since the retransmission of smaller packets is less expensive than large packets in bandwidth utilization. However, when fragmentation are used, the overhead of control information as a fraction of the whole data packets (such as source/destination address, error correction code, etc.) will hereby increase. So the actual throughput is decreased.
- Forward Error Correcting (FEC) [45]. The most obvious way to overcome transmission errors is to use FEC. FEC is more efficient and powerful than Cyclic Redundancy Check (CRC) which just detects errors. FEC adds in every transmission some additional redundancy bits. Depending on the number of bits added and the FEC code used (the strength of the code), this allows to repair a certain number of errors in the transmission. However, FEC tends to be ineffective against fading and interferers in wireless network context.
- Retransmission Methods [46]. MAC protocols implement positive acknowledgement and MAC level retransmissions to avoid packet loss. If error correcting code is not used

at destination side or it is not able to recover packets from error, packets have to be retransmitted from the source to the destination after an acknowledgement timeout.

Packet retransmission is the widely used strategy for error recovery, since it is effective and easy to be implemented. Upon reception of a packet, the destination station sends back immediately an ACK message to the source station to indicate that it has successfully received the packet without errors. If an ACK is not received at the end of a transmission within the predefined timeout threshold, the packet is retransmitted by the source station. Obviously, packet retransmission is consider a significant source of power wastage.

2.2.2 Collision Avoidance Mechanisms

On a share transmission medium, when only one station makes a transmission attempt, the data packet is delivered successfully. When multiple stations make transmission attempts while within each other's transmission range, collision may render the simultaneous packets transmission error. Nodes resolve the collisions in an orderly fashion according to rules defined by the contention resolution algorithm. As it has been discussed in previous chapter, the design of most radio transceiver only allow half-duplex communication on a single frequency. Collision Detection (CD) as widely used in wired Ethernet can not be implemented in the MANET. To reduce the cost and complexity of hardware and software design, a single radio channel is often shared among many user in wireless network. This often leads to interference among concurrent transmissions. The result of interferences is that packets collide with interference signal and can be corrupted. Actually, one of the fundamental tasks of any MAC protocol is to avoid collisions so that interfering nodes do not transmit at the same time.

The simplest methods for collision avoidance in a general network include CDMA, Time Division Multiple Access (TDMA), and Frequency Division Multiple Access (FDMA). FDMA divides the available frequency band into multiple non-overlapping channels that are sufficiently separated to prevent co-channel interference. Stations access the media at the same time but

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operate on different frequency channels. TDMA divides the entire channel bandwidth into equal time slots that are then organized into a synchronized frame. Stations share the same frequency band but access the media at different time slots. CDMA allows simultaneous transmissions to coexist on the same frequency channel at the same time by allocating each transmission a unique orthogonal code. These protocols are also known as the scheduling based mechanism, in which the assignment in time, frequency or code domain has to be predefined. The schedule can be expensive and complicated to setup and maintain, which may not be adaptive to the dynamic nature of MANET.

Nevertheless, MAC protocols in MANET are often required to operate in a distributed manner, which makes collision avoidance to be very challenging. In order to efficiently share the transmission medium dynamically among participating mobile stations, the contention-based, random access MAC protocols prove to be simple and effective. Most of the random access MAC protocols utilize Carrier Sensing Multiple Access (CSMA) to avoid collisions with ongoing transmissions. The basic operation principle of any CSMA protocol is described as follows: A node that has data to transmit senses the channel for a certain duration before transmitting. If the channel is busy, the node waits a random period and tries to transmit at a later time. If the channel is idle, the node makes an attempt to acquire the channel. Successful acquisition is followed by transmission of the data packet. If the acquisition attempt results in a collision, the colliding nodes try to resolve the collision in an orderly manner. So the collision is only caused by the control packets that try to acquire the medium, which is much smaller than actual data packets. Each packet transmission is then acknowledged by the destination station through explicit or passive acknowledgement. Collision Avoidance (CA) is achieved by introducing randomized backoff time before transmitting packets after an idle channel is detected. CSMA/CA has satisfactory performance when all stations are within sensing range of each other. Otherwise, hidden terminal problem can occur in ad-hoc networks where the radio range is not large enough to allow communication between arbitrary stations [47].

Figure 2.2: Hidden Terminals that Lead to Packet Collision

A hidden node [48] is one that is within the range of the intended destination but out of range of the sender. Consider the case shown in Figure 2.2, node A is transmitting to node B. Node C cannot hear the transmission from A. During this transmission when C senses the channel, it falsely thinks that the channel is idle. If node C starts a transmission, it interferes with the data reception at B. In this case node C is a hidden node to node A. Hence, hidden nodes can cause collisions on data transmission when CSMA is used.

Although it is impossible to completely eliminate the packet retransmission, various collision avoidance mechanisms can be utilized to reduce the retransmissions caused by collisions. Typically, there are some mechanisms that can be used to enhance the distributed CSMA/CA protocol: the out-of-band approach and the handshaking approach. These approaches are described below.

Collision Avoidance with Out-of-Band Signaling - Busy Tone Multiple Access (BTMA) [49] uses an out-of-band busy tone signal to prevent hidden nodes. Stations must have the capability of communicating using two different frequencies concurrently, the data channel and the signaling channel. Any station that hears an ongoing transmission transmits a busy tone in the frequency other than that used for the data packets; any node that hears a busy tone on the signaling channel does not initiate a transmission. As a result, all stations in a $2R$ radius of the transmitting station are inhibited from transmitting, where R is the range of the transmitting station. Using this solution, collision caused by hidden terminals can be eliminated.

In Receiver Initiated - Busy Tone Multiple Access (RI-BTMA) [50] - a node transmits a busy tone only after it decodes the transmission and identifies itself as the intended receiver. As

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a result, only the nodes within radius R of the receiving node are inhibited. In RI-BTMA the destination has to decode and match the destination address to detect a collision. As a result it takes a long time to initiate the busy tone. Therefore, the packet transmission is vulnerable to collision for a duration much longer than the round trip. This results in a higher probability of collision and hence lower throughput. RI-BTMA does not completely eliminate hidden nodes but minimizes exposed nodes.

Using the out-of-band approach requires that a signaling channel is reserved that solely serves the purpose of collision avoidance control message. It is not an efficient way to use the limited radio resources, and the hardware complexity is increased since two independent sets of radio transceiver are required which is also not power efficient.

Collision Avoidance with Control Handshaking - Multiple Access with Collision Avoidance (MACA) [51] uses a three-way handshake as a solution to the hidden terminal problem. A station that has data to send transmits a short Request to Send (RTS) packet. All stations within one hop of the source hear the RTS and defer their transmissions. The destination responds with a Clear to Send (CTS) message. All stations within one hop of the destination hear the CTS and also defer their transmissions. On receiving the CTS the transmitting node assumes that the channel is acquired and initiates the data transmission. MACAW [52] is an enhancement of MACA that utilize a RTS-CTS-DS(Data Sending)-Data-ACK message exchange and a new back-off algorithm. This handshaking mechanism does not completely solve the hidden terminal problem, but it does prevent it to a large extent. For example, in Figure 2.2, after A and B exchange RTS/CTS messages, A begins to transmit a data packet to B. At the same time, D wants to send a data packet to C and initiate a RTS/CTS handshake. Though C is allowed to receive the data packet from D since it doesn't conflict with the transmission from A to B, C is NOT permitted to access the channel and answer D's RTS message since it has received B's CTS message. The network performance is degraded. In control handshaking based collision avoidance protocols, the control messages that used to acquire the channel

are considered as extra overhead to the data packets. Bandwidth is not fully utilized due to exchanging of many control messages. Furthermore, as stations have to pend the data transmission until the control messages have been successfully exchanged, longer delay of data packets is also expected. In some scenario, station may forever wait and not able to transmit the data packets.

Furthermore, the primary characteristic of an ad hoc network architecture is the absence of any predefined structure. Service coverage and network connectivity are defined solely by node proximity and the prevailing RF propagation characteristics. Considering that most ad hoc systems are fully mobile in which each node moves independently and continuously, the level of the protocol complexity is very high.

2.2.3 Basic Approaches of MAC Level Energy Conservation

This section gives the basic information about the principle of radio transmission and its relationship to the power consumption of wireless communication devices.

2.2.3.1 Radio propagation characteristic and Transmit Power Control

In order to understand MAC level power conservation mechanism, it is necessary to first have an insight of functionality of typical wireless device.

Wireless devices use the modulated radio signal to carry the data information. The propagation of the radio transmission is influenced by many factors. Typically, obstacles between the line-of-sight transmission tend to decrease and reflect the signal, and all kinds of background noise and interference makes it more difficult to identify the originally transmitted signal. So in order to maintain a high SNR at the destination to correctly distinguish and demodulate the radio signal, the transmitted power should be above certain threshold value in order to overcome the path-loss influence and interference. To be more specific, the signal strength of a radio transmission rapidly attenuates as it progresses away from the transmitter. This means that the ability to detect and receive transmission is dependent on the distance between the

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radio transceivers of sender and the receiver [31]. Basic transmission loss, or path loss (PL), is the signal attenuation between transmit (T_X) and receive (R_X) antennas due to the T_X to R_X separation and multi-path (scattering). Basic transmission loss determines the range of a wireless link, which means beyond the transmission range correct demodulation of the signal is often not guaranteed. In free space, radio signals propagate as light dose (independent of their frequency). A signal transmitted with power P_t over a wireless link with distance D gets attenuated and is received with power

$$P_r \propto \frac{P_t}{D^k} (K \geq 2) \quad (\text{Eq. 2.1})$$

where K is a constant called the path-loss exponent that depends on the propagation medium and antenna characteristic [53]. Generally speaking, the path-loss exponent is 2 for ideal free space and line-of-sight transmission. However, a single line-of-sight path between two mobile nodes is seldom the only means of propagation. The two-ray ground reflection model considering both the direct path and a ground reflection path is often used to model out-door transmission with path-loss exponent equal to 4. The two-ray ground model shows a faster power loss than free space model as distance increases. However, The two-ray model does not give a good result for a short distance due to the oscillation caused by the constructive and destructive combination of the two rays. Instead, the free space model is still used when distance is small. Therefore, the transmitted power for a chosen link should be proportional to D^K .

To simplify the design of hardware and software and minimize the cost, a fixed and properly chosen transmit power of a wireless network interface can be assigned by hardware manufacture according to the hardware capability and user requirements. One simple solution is that each station can use its maximum power level, which increase the communication range and improve the received signal quality. However, it also introduces various counteractive effects which make it difficult to decide the trade-off in a distributed communication environment:

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- (i) Using maximum power level for communication leads to excessive energy consumption that shortens the battery operation time.
- (ii) The increased communication range leads to a large number of neighboring stations on average. The overhead of maintaining neighboring information is not negligible.
- (iii) The topology will have excessive interference and less opportunity for spatial reuse, which can severely limit the aggregate throughput.

The other extreme approach is to use a small power level at each station, which may reduce the connectivity and lead to network partition.

Figure 2.3: Dynamic transmission power adjustment

Based on the above discussion, dynamic adjustment of transmit power according to the distance between the sender and receiver can be an effective way to avoid unnecessary power waste [54] and increase spatial reuse. Instead of using a common high transmit power, stations can have asymmetrical transmit power levels which differentiate the transmission range accordingly. As shown in Figure 2.3, station B can use power level-2 to communicate with station A instead of power level-1 to save energy, where power level-2 is significantly less than power level-1. This intelligent transmission power adjustment not only save considerable amount of energy, but also reduce the radio interference and collision probability. In the scenario shown in Figure 2.3, when power control is employed, the transmission $A \leftrightarrow B$ and $C \leftrightarrow D$ can go along concurrently

without interfering with each other. Therefore, network performance, such as throughput, is also increased. Such control mechanisms are often referred as the topology control protocol that have been investigated in [55, 56, 57].

Power Control MAC (PCM) protocol [58] is an example of dynamic transmission power adjustment that allows per-packet selection of transmit power. In PCM, RTS/CTS packets are transmitted with a max power level, P_{max} . Data packets are transmitted with a lower power level. During the DATA packet transmission PCM periodically increases the transmission power to P_{max} as a busy tone signal to nearby stations. ACK packets are transmitted with the minimum required power to reach the source node. By periodically increasing the power level for data transmission, PCM effectively reduces the amount of possible collisions. However, PCM requires a frequent increase and decrease in transmission power levels, hence the implementation is not easy.

Power Controlled Multiple Access (PCMA) protocol [59] proposes a flexible collision suppression model and allows variable transmit power levels on a per-packet basis. PCMA uses RPTS/APTS handshake on data channel to determine the minimal transmission power required for successful packet reception. During the data packet transmission, each active receiver will periodically send a busy tone to advertise the maximum additional noise power it can tolerate. A potential transmitter first monitors the control channel by listening to the busy tone for a minimum time period to detect the upper bound of its transmit power for all control (RPTS, APTS, ACK) and data packets. Through the exchange of noise tolerance advertisement, power control mechanism is realized and spatial reuse is achieved.

2.2.3.2 Operation States of the Wireless Transceiver

Despite that the transmission range is closely related to the power consumption, mobile devices consume distinct amount of energy in different operation states. The wireless network interface can operate in transmit state, receive state and idle state (any of these three states is considered as an active mode), or in doze mode (also known as Power Saving (PS) mode) [5]. The wireless

interface is fully powered in active mode and is able to transmit and receive packets at any time or wait in idle state (although wireless interface consumes different amount of power in each of these three states, it is significantly more than the power in PS mode). Figure 2.4 is the power consumption investigation of a typical wireless network interface card in different operation state. Furthermore the function in MAC protocol supported by physical layer design is capable of switching the wireless interface in either the active or the PS mode at any time for the basic communication need.

- (i) Transmit—Transmit power is the power required at the sender to transmit a packet. Transmit power primarily depends on the distance between the source and the destination and is given by Eq. 2.1. In general, transmit power also depends on the desired reliability and is greater for more reliable communication. Transmit power provides a tradeoff between communication range and energy consumption. This provides a higher degree of freedom in optimizing at the cost of complex algorithms for power control.
- (ii) Receive—This is the amount of power required to receive one packet. It is normally a constant value and depends on the radio technology. For most of the commercially available wireless devices, the receive power is comparable to the transmit power.
- (iii) Listen—In this mode, the transceiver constantly monitors the wireless channel status and detects incoming packets. Power consumed in the listen state is substantial and is close to the receive power. Reducing the idle listening time is one of the most effective mechanism to improve the channel utilization and energy efficiency.
- (iv) Sleep—In this mode, almost all of the circuitry is powered off and the radio can not perform any function. Power consumption is very low in this state.

Even in the idle state, the network interface still consumes significant amount of energy, about 20 times more than the PS state. It is not power efficient to leave the node in idle state

Figure 2.4: Power consumption of wireless network interface card in different operation state

when it will not be involved in the data packet transmission for a long time. Energy efficient MAC protocols can switch the wireless interface to the PS state instead of staying in active state when specific station is not expected to participate in the data transmission for a long time. Energy efficiency can be achieved due to the multiple access of wireless medium (i.e., time slot, frequency, and CDMA code) among many users, which leads to a long waiting time in the idle state because of contending and deferring access to the wireless medium. The utilization of the power saving mode and the power state transition are the basic power conservation principle used in IEEE 802.11 based wireless LAN.

Power saving mode of IEEE 802.11 distributed coordinated function - IEEE 802.11 protocol for wireless LAN is multiple access technique based on CSMA/CA [52]. 802.11 protocol specifies a DCF mode which is designed for the so-called ad hoc communication scenario without any predefined infrastructure. This mode of operation is possible when IEEE 802.11 stations are able to communicate directly, and the coverage area is defined as the IBSS. As this type of IEEE 802.11 LAN is often formed without pre-planning, for only as long as the LAN is needed, the operation is often referred to as an Ad Hoc network.

The media access procedure is based on DFWMAC which is a derivative of the MACA [51] protocol. It consists of a two-way packet exchange, DATA-ACK; or optionally four-way exchange, RTS-CTS-DATA-ACK. RTS and CTS are control packets that try to eliminate the hidden nodes as described before. The four-way handshaking is illustrated in Figure 2.5. When

Figure 2.5: DCF access procedure of IEEE 802.11

a station (sender) has data to transmit, and the wireless medium is detected as idle for more than Distributed Inter Frame Space (DIFS), the station will transmit the data immediately. Otherwise the medium is occupied by other ongoing transmission, the station has to defer the access to the wireless channel to avoid collision. It picks a random wait period by calculating a random backoff counter within the range of $[0, CW - 1]$ slots time (CW is the contention window size used in the backoff mechanism). This backoff counter is decremented by 1 when the channel is detected as idle for one slot time. When the backoff counter expires, the station tries to acquire the channel by sending a RTS packet. As for a busy channel, the backoff counter remains the same. The receiving node (destination) responds with a CTS packet indicating that it is ready to receive the data. The sender then completes the packet transmission. If this packet is received without errors, the destination node responds with an ACK. If an ACK is not received, the packet is assumed to be lost. The sender has to retransmit the packet. If the RTS fails, the node attempts to resolve the collision by doubling the contention window size. This contention resolution method is called binary exponential backoff.

In the IEEE 802.11 Power Saving (PS) mode specified for DCF, it is assumed that all nodes in the same IBSS are fully connected, so all nodes can hear each other's communication. In such a single-hop ad-hoc network scenario, time synchronization is easily achieved by periodically sending certain special frame called beacon. Transmission time is therefore divided into so-called Beacon Interval. At the start of each beacon interval, each node in the PS mode periodically

wakes up for a duration known as Announcement Traffic Indication Message (ATIM) Window and TSF beacon is sent at the beginning of each ATIM window. As a result of synchronization, the ATIM window will be a common awake period for all the nodes within the IBSS. At the beginning of an ATIM window, each mobile host will contend to send the beacon frame. The successful beacon serves the purpose of synchronizing all mobile hosts' clocks. This beacon also inhibits other hosts from sending their beacons. To avoid collisions among beacons, a host should wait a random number of slots between 0 and $2 \times CW_{min} - 1$ before sending out its beacon. After the beacon, a host with buffered unicast packets can send a direct ATIM frame to each of its intended receivers in PS mode. ATIM frames are also transmitted by contention based on the DCF access procedure. After successfully transmitting an ATIM frame, the mobile host will remain awake for the entire remaining period. On reception of the ATIM frame, the PS station should reply with an ACK and remains active for the remaining period. The buffered unicast packets would be transmitted based on the normal DCF access procedure after the ATIM window finishes. If the sender does not receive an ACK, it should retry in the next ATIM window. As for buffered broadcast packets, the ATIM frames need not to be acknowledged. Broadcast packets can then be sent based on contention after the ATIM window finishes. If a mobile host is unable to transmit its ATIM frame in the current ATIM window or has extra buffered packets, it should retransmit ATIMs in the next ATIM window. To protect PS hosts, only RTS, CTS, ACK, Beacon, and ATIM frames can be transmitted within the ATIM window. Even in the idle state, node still consumes significant amount of energy, about 20 times more than the PS state. It is not power efficient to leave the node in idle state when it will not be involved in the data packet transmission for a long time. IEEE 802.11 PS mode utilizes the ATIM window to announce the traffic using small ATIM frames. Hence nodes can switch to the PS state instead of staying active till the beginning of next beacon interval, because it can decide whether it will participate in any transmission in the rest of the beacon interval based on its local information and the ATIM announcement packets it has received.

Figure 2.6: Power saving mode of IEEE 802.11 DCF mode

Figure 2.6 shows an example, where station A wants to transmit a packet to station C. During the ATIM window, an ATIM frame is sent from A to C. C responds with an ACK. After the ATIM window finishes, A can try to transmit its data packets to C. It is obvious that node B has saved energy by switching itself to the PS state.

Figure 2.7: Power consumption saved in MANET by dynamically switching off the network interface

In [60] a power-conserving algorithm is introduced by dynamically switching off the node's radio transceiver based on the RTS/CTS dialogue of the IEEE 802.11 standard. When a node detects an RTS/CTS handshake and if it is not involved, it will power off the wireless radio transceiver for the duration of the data packet transmission (directly available in the Duration/ID field of the RTS/CTS packets). However, the frequently node state transition (per

packet basis) may forfeit the energy saving when the cost of state transitions is non-negligible. Figure 2.7 shows an example that the power waste due to overhearing can be reduced by switching off the radio transceiver.

Power Aware Multi Access (PAMAS) protocol [61] was designed for the ad hoc network, with energy efficiency as the primary design goal. In PAMAS, each node uses two separate channels for control signaling packet and data packet transmissions. Each node can know if a direct neighbor is transmitting through overhearing of the data channel. Similarly, through the control channel, each node can also know if one or more of its neighbors are receiving, because the receiver will transmit a busy tone through the control channel when it begins to receive a packet. In both the scenarios described above, a node can intelligently turn off the radio transceiver to save energy instead of staying in the idle state. This scheme has the disadvantage of requiring two channels for communication.

An energy-efficient MAC protocol for wireless sensor networks, called S-MAC is proposed in [62]. S-MAC uses periodic listen and sleep to reduce the energy consumption by avoiding idle listening. Synchronization among neighboring stations are required. S-MAC uses synchronization to form virtual clusters of nodes on the same sleep schedule. S-MAC uses the in-channel signaling to put the stations in sleep mode when its neighboring node is in transmission. The in-channel signaling helps reduce the overhearing problem and avoids the use of additional channel resource.

2.2.4 Power Efficient MAC Protocol

In this section, a brief review of the power efficient MAC protocol used in the wireless communication environment is presented. As illustrated in Figure 2.8, wireless MAC protocols can be broadly classified into two categories, distributed and centralized, according to the type of network architecture for which they are designed. Furthermore, the power saving mode specified for IEEE 802.11 will be introduced, and the existing modifications and amendments to 802.11 that aim to achieve energy efficiency will also be review extensively.

Figure 2.8: Classification of wireless MAC protocols

The typical protocols of the categories mentioned above will be exemplified, respectively.

Random access protocols

EY-NPMA - EY-NPMA [63] is the channel access protocol used in the HIPERLAN system developed in Europe. HIPERLAN is a high-speed (24 Mb/s) wireless LAN standard for distributed networks. The protocol operates as follows: A node that has data to transmit senses the medium for a period corresponding to the time it takes to transmit 1700 bits. If no transmission is heard the channel is considered idle and the node can start transmitting its packet immediately. If the channel is busy the node synchronizes itself at the end of the current transmission interval and contends for the channel according to rules described below. The access protocol is illustrated in Figure 2.9. The channel access has three phases: prioritization phase (the priority is decided), contention phase (nodes of the same priority contend and one station wins), and transmission phase (succeeding station completes the data transmission). The contention phase consists of two sub-phases: elimination phase and yield phase. In the elimination phase each node transmits for a random number of slots (the random number is picked according to a geometric distribution). At the end of the elimination phase, the node turns around and listens to the channel. If the channel is busy, it aborts its transmission attempt. If the channel is idle the node moves to the yield phase. In this phase it listens to the channel for a random number of slots. If no transmission is detected during this time, the station starts and completes its data transmission. The distributions for the random numbers

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are chosen such that the probability of a single transmission at the end of contention phase is very large (close to 1). The priority of a packet is derived from its Normalized MAC PDU Residual Lifetime (NMRL). NMRL is the time that the packet has been in the queue waiting to be transmitted. The more the packet is delayed, the higher is its priority.

Figure 2.9: Operation of EY-NPMA

HiperLan uses the 5.2 GHz frequency band to achieve a much higher bandwidth. The physical layer can offer different data rates, the low data rate (1.4706 Mbits/s) and a high data rate (23.5294 Mbits/s). When operating in the high data rate mode, an equalizer is required and energy consumption is very high. In order to save power, each packet is also divided into a low-bit-rate and high-bit-rate parts. Address information is encoded in the low-bit-rate part. On reception of the address information, a mobile can decide whether it is the destination. If not, it will not turn on the equalizer to receive the high-bit-rate part, which conserves considerable amount of energy.

Centralized MAC protocol

The centralized structure, consisting of the base station and several mobile devices, and is inherently more suitable low power design. The reason for this is that the base station equipped with intelligent and sophisticated hardware is normally fixed to a certain place that has a continuous power supply. All communications are scheduled by the centralized authority, therefore, collisions over wireless channel are avoided. Hence packet retransmission, which is

considered as a waste of energy, can be dramatically reduced. Furthermore, mobile devices are not required to monitor the transmission channel as the result of communication schedules, which can reduce a significant amount of energy consumption caused by the overhearing of other's transmission. The centralized scheduler may also optimize the transmission schedule so that energy efficiency and network performance are improved directly. The drawback of this method is the limited flexibility because the infrastructure has to be setup in advance compared to the distributed system, and mobiles cannot communicate out of the coverage of the base station, even they are very close to each other. In addition, since all packets are transmitted through the central control unit, each data packet is to be transmitted twice to reach its destination (Mobile→Base station→Mobile) instead of once in distributed mode (Mobile→Mobile) [64].

PCF of IEEE 802.11 - PCF is a centralized, polling-based access mechanism which requires the presence of an AP that acts as Point Coordinator (PC). PCF is an extension that on top of DCF mode and provides two different type of services:

- (i) Contention-free channel access for the AP to deliver the frames on the down link. This service is utilized to allow the AP to transmit any buffered traffic coming from the wired LAN part to the mobiles.
- (ii) Contention free service for the mobiles to support time bounded traffic.

Contention-free service is provided by using an additional inter-frame space called Point Coordination Inter Frame Space (PIFS) where $SIFS < PIFS < DIFS$. It is used by the AP to gain and retain control of the wireless channel. Because PIFS is less than DIFS used by mobiles, so AP will have higher priority of gaining access to the channel by deferring less time if the idle medium is detected.

In order to integrate DCF and PCF together seamlessly, time is divided into superframes in the PCF mode as shown in Figure 2.10. Each superframe consists of a contention period

Figure 2.10: Super frame structure of IEEE 802.11 PCF

where DCF is used and a Contention Free Period (CFP) where PCF is used. The CFP is started by a beacon frame sent by the PC using DCF. The CFP may vary from superframe to superframe, as the base station has to contend for the medium. Once the CFP starts, the PC polls each station in its polling list (the high priority stations) when they can access the medium. To ensure that no DCF stations are able to interrupt this mode of operation, the inter frame space between PCF data frames PIFS is shorter than the DIFS. To prevent starvation of stations that are not allowed to send during the CFP, there must always be room for at least one maximum length frame to be sent during the contention period. The PC polls the stations in a round-robin fashion. A polled station always responds to a poll. If there is no pending transmission, the response is a null frame containing no payload. If the CFP terminates before all stations have been polled, the polling list is resumed at the next station in the following CFP cycle. A typical medium access sequence during PCF is shown in Figure 2.11. A station being polled is allowed to transmit a data frame. In case of an unsuccessful transmission, the station retransmits the frame after being re-polled or during the next Contention Period.

Energy Conserving Medium Access Control (EC-MAC) - In EC-MAC [65], a single base station is used for centralized schedule. Transmission is organized into frame by the base station. At the start of each frame, the base station will transmit the Frame Synchronization Message (FSM), which contains synchronization information and the uplink transmission order. The request/update phase follows next, each registered node transmits new connection request

Figure 2.11: Example of PCF frame transfer of IEEE 802.11

and the status of established queue order according to the transmission order received from the FSM. Then, the base station sends out schedule information and the rest of the time is divided into Data phase (downlink) and Data phase (uplink) to reduce collision and turn around of the node state. Energy consumption is reduced in EC-MAC because of the use of a centralized scheduler to reduce collision and monitor the wireless channel. In this protocol, a base station is needed as part of the infrastructure.

Figure 2.12: EC-MAC protocol frame structure

2.2.5 Modification to the power saving mode of IEEE 802.11

IEEE 802.11 protocol has attracted a lot of research interests. some modification to the IEEE 802.11 protocol will be described that optimized to achieve more energy efficiency.

SPAN [66] is a power saving technique that takes advantage of the backbone network.

Figure 2.13: Coordinator selection in SPAN

Basically, in a connected network, not all nodes have to stay active to maintain the network connectivity. As shown in Figure 2.13, the stations represented by black spots are always active to guarantee the network connectivity. SPAN adaptively elects a group of such coordinators from all nodes in the network and rotates them in time. The coordinators always stay active and perform multi-hop packet routing within the ad-hoc network. Non-coordinators follow the power saving mechanism in IEEE 802.11. Nodes buffer the packets for the destinations in PS state and announce these packets during ATIM window. SPAN has modified the PS mode specified in 802.11 by introducing a new advertised traffic window, which starts at the beginning of the beacon interval and extends beyond the ATIM window. Outside the ATIM window but inside the advertised traffic window, the announced packets and the packets for the coordinators can be transmitted. After this window, only the packets for the coordinators can be transmitted, and non-coordinators can switch to PS state if they will not be involved in the data packet transmission till the beginning of the next beacon interval.

[67] proposed a modification to the power saving mode of IEEE 802.11 by dynamic adjustment of the ATIM window size, named Dynamic Power Saving Mechanism. As introduced in previous section, IEEE 802.11 power saving mode utilizes ATIM window as a common awake period for all the stations within the IBSS to exchange control information. Data packets have to be announced first during the ATIM window. Once the announcement is successfully acknowledged by the intended destination, both the sender and the receiver have to stay in the active state during the rest of the beacon interval for the transmission of the data packets.

While others stations that do not participate in any transmission can switch to the power saving state to save energy. Since the ATIM window size critically affects throughput and energy consumption, a fixed ATIM window does not perform well in all situations, as shown in [68]. If the ATIM window is chosen to be too small, there may not be enough time available to announce buffered packets (by transmitting ATIM frames), potentially degrading throughput. If the ATIM window is too large, there would be less time for the actual data transmission, again degrading throughput at high loads. Large ATIM windows can also result in higher energy consumption since all nodes remain awake during the ATIM window. At low load, in particular, large ATIM windows are unnecessary.

Figure 2.14: Dynamic ATIM window size adjustment of DPSP

In Dynamic-Power Saving Mode (PSM), stations can dynamically adjust the ATIM window independently based on observed network conditions as shown in Figure 2.14. ATIM window values varies between 2 ms and 26 ms, in increments of 2 ms. stations can increase the ATIM window size to the next level if any of the rules listed below are satisfied.

- (i) Based on the number of pending packets that could not be announced during the ATIM window.
- (ii) Based on overheard information. Each node piggybacks its ATIM window size on all transmitted packets. If a node overhears an ATIM window size that is at least two levels

larger than that being used by node A, then node A increases its own ATIM window size by one level.

- (iii) Receiving an ATIM frame after ATIM window.
- (iv) Receiving a marked packet. A marked packet indicates failure to deliver the corresponding ATIM frame in a small number of attempts C this might indicate that the recipient node is using too small ATIM window.

Dynamic-PSM is based on PSM, but a node can dynamically adapt its ATIM window size according to observed network conditions. In Dynamic-PSM, a node can also power off its wireless network interface whenever it finishes packet transmission for the announced packets.

In [69], a distributed power-saving protocol Power-Efficient MAC (PEM), to avoid collisions and to save energy is proposed. PEM takes advantage of power control technique to reduce the interferences among transmission pairs and increase the spatial reuse of WLANs. Based on the concept of Maximum Independent Set (MIS), a novel heuristic scheme with the aid of interference relationship is used to provide as many simultaneous transmission pairs as possible. In PEM, all stations know when to wake up and when they can enter doze state. Stations need not waste power to idle listen and can save much power.

In [70], an enhancement to the standard IEEE 802.11 MAC protocol is proposed by improving the handshaking mechanisms and adding one separate power control channel. With the control channel, the receiver notifies its noise tolerance to all neighbors. Thus, the neighbors can adjust their transmission power levels to avoid packet collisions at the receiver. The network throughput can be increased, and the battery utilization can also be improved at the same time.

Chapter 3

A Modified Power Saving Mode in IEEE 802.11 Distributed Coordinator Function

Power saving (PS) mode specified in IEEE 802.11 standard is a power efficient method that prolongs the network operation time of battery powered wireless LAN devices. It is a synchronous protocol which requires precise time synchronization among all the participating mobile stations within the IBSS. Therefore, TSF is defined for the protocol to operate without the aid of external timing sources. Time synchronization is achieved by periodically transmitting the time synchronization beacon, which will define a series of fixed length beacon intervals. In PS mode for DCF, mobile stations will wake up at the beginning of each beacon interval for a duration called ATIM window to announce their pending data packets using small ATIM control packets. After the ATIM window, mobile stations will transmit the announced data packets using contention-based DCF access procedure. This chapter proposes a modified mechanism by sending the TSF beacon at the end of each ATIM window and adding certain scheduling information in the beacon to schedule the transmission of announced data packets. The scheduling information will ensure the data packets transmission to be contention-free. Hence the scheduled data packet transmission will achieve a higher throughput and lower energy consumption [9]. Results based on simulation have shown that as much as 70% of energy saving can be achieved.

This chapter is based on the following paper:

M. H. Ye, C. T. Lau and A. B. Premkumar, "Modified Power Saving Mode in IEEE 802.11 Distributed Coordinator Function", in *Performance issues of Wireless LANs, PANs and ad hoc networks*, Elsevier Computer Communications, Volume 28, Issue 10, Pages 1214-1224, June 2005.

3.1 Introduction

With the rapid development of wireless communication technology, computing and communication anytime, anywhere and to anybody else is made possible by providing the wireless networking facility to all kinds of mobile devices. These wireless devices are often powered by batteries in order to achieve mobility and flexibility. Furthermore, transmitting and receiving data through the wireless radio transceiver is costly from the energy consumption perspective, especially when a random-access wireless radio channel is shared among many users. Due to the constraint of weight and capacity, batteries can provide only a finite amount of energy. Unless there is a significant break through in battery technology, research on power-efficient method is always worthwhile.

As one of the most popular wireless technology, Bluetooth [6] is characterized by its inexpensiveness and high availability, but it is only considered as a cable-replacement alternative because of a relatively small bandwidth and short communication range. With the growing demand for bandwidth, IEEE 802.11 based wireless LAN [1] is gaining an important role in the development of wireless network. With the increased transmission range and high speed transmission capability, IEEE 802.11 based wireless LAN leads to a high energy consumption [71, 72] which contributes to as much as 20% of the total energy consumption of a laptop computer equipped with wireless network interface[20, 21]. However, as far as handheld devices are concerned, the power consumption of communication is even more significant, because typically handheld devices are not equipped with hard disk and the screen is much smaller than laptop computers [23].

CHAPTER 3. A MODIFIED POWER SAVING MODE IN IEEE 802.11 DISTRIBUTED COORDINATOR FUNCTION

Understanding of the power consumption model of mobile radio used in wireless devices is important for efficient design of communication protocols. A wireless interface can be in transmit state, receive state, idle state (any of these three states is considered as an active mode), or in doze state (also known as PS mode). As denoted in IEEE 802.11 [1], a station is fully powered in active mode and is able to transmit and receive packets at any time or wait in an idle state. According to [5, 73], it is found that even in the idle state significant power is consumed (about 20 times more than the PS mode) while listening to the transmission of other stations and monitoring the channel, which is considered as a major power wastage [60]. The basic idea in power saving is to put the mobile station in PS mode as long as possible without affecting the network performance and connectivity.

The power saving mechanism specified for DCF is a power efficient mechanism operating in a totally distributed manner. Time synchronization is required to decide the start and end time of each beacon interval, as well as the ATIM window which is a common awake period for all the mobile stations within the IBSS. The ATIM window is utilized to announce the pending data packets using small control frames. During the rest of beacon period all mobile stations that have transmitted ATIM announcement and have received the ATIM ACK will have to contend for the medium using standard DCF access procedure to send their multicast/broadcast or unicast data packets. In this chapter, a scheduling mechanism is introduced by having a mobile station functions as the centralized scheduler to send out the TSF beacon along with explicit transmission ordering information at the end of ATIM window. This mechanism organizes the data packet transmission phase to achieve the benefit of centralized protocol. The proposed protocol takes advantage of centralized scheduler. However, all mobile stations operate under the distributed mode and no infrastructure is required.

The rest of this chapter is organized as follows. Section 3.2 presents a detailed overview of existing power saving mode specified for DCF of IEEE 802.11 and related power saving mechanisms for wireless network. The proposed modification of IEEE 802.11 DCF power saving

mode is presented in Section 3.3 . Simulation results and performance comparison are shown in Section 3.4. The analysis and discussion are given in Section 3.5. Conclusion will be addressed in Section 3.6.

3.2 Related Works

In [74], a novel energy efficient communication strategy is proposed, named as Self-Protective Transmit Power Control (SP-TPC), for IEEE 802.11 Wireless LANs. SP-TPC utilizes both TPC and PHY layer rate adaptation in order to minimize the communication energy consumption while maximizing the throughput performance. When the TPC is employed in the 802.11 WLAN, the overall performance may be degraded due to the potential increase of hidden stations, and hence the RTS/CTS exchange is typically used in conjunction with the TPC in order to eliminate hidden stations. However, the RTS/CTS exchange is an expensive solution since this consumes additional energy as well as the precious bandwidth. By taking advantage of the existing Clear Channel Assessment (CCA) mechanism intelligently, SP-TPC does not introduce any extra hidden stations, and hence the RTS/CTS exchange is not needed if hidden stations did not exist without TPC.

In [75], an analytical model to investigate the energy efficiency of 802.11 DCF is introduced. It shows that factors such as the number of contending mobile stations, packet size, contention window, packet transmission collision probability and channel condition affect the energy efficiency of 802.11 DCF significantly [76]. Energy efficiency optimizations via optimal contention window and via optimal packet size are compared under various channel conditions and network configurations, which helps to identify the tradeoff in choosing packet size to optimize the energy efficiency of DCF in error-prone environment. It is shown that under error-prone environments optimal packet size can improve more on the energy efficiency than optimal contention window. Combining both optimal contention window and optimal packet size can achieve the maximum optimization.

In [77], a novel energy-saving MAC layer scheme is proposed. The proposed scheme enables a wireless station to enter the power saving state, while the Network Allocation Vector (NAV) is set as well as during the backoff time interval. They assumed that the mobile stations can read the frame duration field in the frame header and set their NAV. Mobile stations do not need to sense the channel while being in backoff but it can be in doze state. When the backoff counter reaches zero, the mobile station behaves as in the DCF scheme specified in the IEEE 802.11 standard. They use a fixed state machine to control the mobile stations' transition from the active state to the PS state and vice-versa, which enables a station to enter the doze state during channel contention by exploiting the virtual carrier sense mechanism and the backoff function.

[78] proposed a data rate selection protocol which selects the best available data rate to transmit messages. After the data transmission rate has been selected, each transmission is scheduled according to the data transmission rate and the packet size. ATIM frame is transmitted with the lowest data rate (say 1Mbps). The destination station determine the desired data rate for data packets based on the SNR of incoming ATIM frame. Their objective is to minimize the average waiting time of each transmission and thus the PS hosts can switch back to power-saving mode as soon as possible. Therefore, they use the shortest job first policy to let the transmission with shortest transmission time to access the channel first. By setting the transmission's backoff timer according to the priority, the transmission with the highest priority will have the shortest backoff time and thus can access the channel first.

In [79], the authors proposed three asynchronous power management protocols for multi-hop MANETs, namely dominating-awake-interval, periodically-fully-awake-interval, and quorum-based protocols. Their protocols allow multiple beacons in a ATIM window in order to obtain more accurate neighbor information by introducing a beacon window. Their protocol also requires that the wake-up patterns of two PS hosts must overlap with each other no matter how much time their clocks drift away, so hosts can overheard others' beacon to derive their

wake-up pattern. Basically, their different approaches are defined based on how long a host should stay active during beacon intervals. However, introducing multiple beacons will lead to high power consumption and collision possibility. If the beacon window is very small, mobile stations can not get enough information on other hosts. If the beacon window is too large, it will reduce effective bandwidth. Our proposed protocol use single beacon with piggyback scheduling information, which is more efficient.

In [80], the authors presented Power Save, Distributed Contention Control (PS-DCC) protocol to enhance IEEE 802.11 DCF. In this paper, the problem of determining the optimal transmission radius for minimal interference and energy consumption is considered. The DCC protocol uses the channel contention status to determine whether to defer current transmission. They also obtain an optimal backoff value from their model using parameter such as number of mobile stations. The protocol is not flexible since it requires prior knowledge of the network status to calculate an optimal backoff model for all mobile stations. It is not adaptive in ad hoc environment where the frequent and undetermined joining and leaving events will simply invalid the prior calculated model.

In [81], the author proposed a Traffic Indication-based Power Saving (TIPS) protocol. In their protocol, if the transmitter issuing a beacon has any data packet to send in its buffer, it tries to transmit the beacon in the earlier time slot(ETS) , otherwise, it tries to delay the transmission time in the later time slot (LTS). If no nodes transmit any beacon in the ETS, all nodes can assume that there are no nodes currently buffering data to send within a present BI and switch to power saving state. They use CW_{min} as the size for ETS and LTS, in which all stations are required to be active. This significantly increase the energy required to transmit beacon and also reduce the available time for ATIM window and data packet transmission. Their protocol is not adaptive to beacon transmission error. When the number of mobile stations is very large and most of them have data packets to transmit, they will contend in ETS and lead to severe collision. If no successful beacon is receive, all mobile stations will assume

no data packet transmission and switch to power saving state. So the actual data packets can not be delivered, which leads to prolonged delay. Furthermore, if above mentioned scenario happens in one BI, then it will even worse in the next BI, since more packets are queued at mobile stations and more station will join the beacon contention in ETS.

3.3 Proposed Modification of IEEE 802.11 DCF PS Mode

This section shows how the existing IEEE 802.11 DCF power saving mode is modified to achieve better performance. In order to implement the scheduling mechanism, the function of the beacon packet in traditional IEEE 802.11 PS mode is modified. A successfully transmitted beacon packet will be received by all mobile stations within the IBSS. Considering this characteristic of the beacon transmission, it is very natural to utilize the centralized schedule through the beacon packets.

It is assumed that mobile stations are capable of operating in the promiscuously listening mode within the ATIM window. Through this listening mode, mobile stations will receive all the ATIM announcements within the ATIM window. In addition, mobile stations will piggyback the number of pending packets (denoted as *NumPacket*) for current destinations in each ATIM announcement packet transmitted. This is the supplementary information that will make the scheduling more efficient.

The following modifications to the beacon generation and beacon transmission will enable the implementation of the scheduling mechanism.

3.3.1 Beacon Transmission

The TSF beacon is moved to the end of the ATIM window as illustrated in Figure 3.1.

- (i) The beacon will carry the scheduling information.

The transmission schedule is computed upon receiving the ATIM announcement information in the ATIM window. The schedule is then announced via beacon transmission

Figure 3.1: Illustration of Scheduled Power Saving Mode

at the end of the ATIM window. In IEEE802.11 specification, the interval between two consecutive beacons is the length of the beacon interval (which is determined by the *BeaconInterval* parameter of the mobile station, abbreviated as *BI* in the following equations).

(ii) The first ATIM window begins at TSF *timer* = 0.

(iii) Subsequently each ATIM window begins when,

$$Timer_{local} \bmod BI = 0 \quad (\text{Eq. 3.1})$$

Within the ATIM window, mobile stations with packets to send will start the transmissions of their ATIM announcements according to the backoff procedure as defined in IEEE 802.11 standard.

(iv) In each of the ATIM window, the mobile station that successfully transmits the first ATIM announcement frame and consequently receives ATIM ACK frame will have to take the responsibility of sending the TSF beacon.

As all mobile stations are fully synchronized by the last beacon received, the next beacon will be sent when the timer reaches a certain predefined time shortly before the end of current

ATIM window (denoted here as the *BeaconTransTime*). All other mobile stations will defer contention for the channel access when

$$Timer_{local} \bmod BI = BeaconTransTime \quad (\text{Eq. 3.2})$$

and will listen to the beacon. In the ATIM window implementation of IEEE 802.11 DCF PS mode, all mobile stations use the backoff mechanism to send the beacon. However, in our implementation the transmission of the beacon is contention-free.

3.3.2 Beacon Generation

The mobile station, which successfully sends the first ATIM announcement in current ATIM window is responsible for the transmission of TSF beacon. It will have to promiscuously listen to the channel for all the ATIM announcement packets. All the multicast/broadcast announcements and unicast announcements with ACK from destinations will be recorded for the scheduling decision. Information needed for decision-making includes source address, destination address, and number of pending packets for current destination. The procedures that govern efficient scheduling will be described in detail in the subsequent sections.

There are some important design issues in generating the beacon:

- (i) The generation of the TSF timer within the beacon is the same as stated in the IEEE802.11 specification.
- (ii) The Beacon will carry transmission-scheduling information that will organize the broadcast/multicast and unicast packets that have been announced during current ATIM window.

Table 3.1: Scheduling Stack

Transmission Order	Source Address	Destination Address	Number of Pending packets
1,2,3...	4 bytes	4 bytes	2 bytes

The structure as shown in Table 3.1 will be used to send out the explicit transmission order to schedule the data packet transmission phase. The order in which each item is stored within this structure determines the sequence of transmission.

3.3.3 Data Packet Transmission

Upon receiving the beacon frame, each mobile station will extract the schedule information and store it locally. Only the mobile stations with their own ID matching the source or destination ID can participate in the data packet transmission. Hence each mobile station will transmit its pending data packets according to the schedule after the end of ATIM window and only one mobile station with its ID matching the source ID in the top of the schedule stack will be in the transmit state. Note that the transmission is not contention based (standard DCF in IEEE802.11), but based on a centralized schedule, which will theoretically achieve contention-free and collision-free transmission.

Each mobile station will decrease the *NumPacket* parameter of the top item in the Scheduling Stack by 1, if any of the following criteria satisfied:

- Finish transmitting an ACK frame for the successfully received data packet (for the destination mobile station).
- Receive an ACK frame before timeout after transmitting the data packet (for the source mobile station).
- Overhear an ACK frame for a data packet (for other mobile stations).

The top item will be removed from the stack if the *NumPacket* parameter is equal to zero.

The transmission of all the packets in a single source-destination pair is the same as IEEE 802.11 DCF when transmitting a multiple-fragmented data unit using the Short Inter Frame Space (SIFS). The DIFS will be used to separate the transmission of two different source-destination pair. Figure 3.2 shows a simple example to illustrate the scheduled data packet transmission.

Figure 3.2: A scheduled data packet transmission

3.3.4 The Power State Transition

In the IEEE802.11 PS mode specification, the mobile stations that have announced pending packets during current ATIM window will have to stay in the active mode for the entire duration of current beacon interval. The main objective of this mechanism is to enable that multiple packets can be transmitted with only one ATIM announcement packet. In our proposed algorithm mobile stations may switch to doze state after they have finished transmitting or receiving the packets to save energy. Since the *NumPacket* parameter announces the traffic condition explicitly, the same objective can be achieved with better power efficiency.

As in the PS mode of IEEE 802.11 DCF, if a mobile station is operating in PS mode, it shall enter the active mode prior to each ATIM window. At the end of each ATIM window, the beacon will serve as the sleeping signal for all mobile stations if and only if the following criteria are satisfied:

- There are no pending unicast packets in the mobile station's transmission queue that have been acknowledged by receiving ATIM ACK packets from the specific destinations or multicast/broadcast packets that have been announced by this mobile station during current ATIM window.
- There are no broadcast or multicast packets announced in the current ATIM window that are destined for this mobile station.

- This mobile station has not sent any ACK for any ATIM announcement packet within current ATIM window.

After each successful transmission of data packets, both the source mobile station and the destination mobile station will use the following criteria to decide whether or not they can return to the doze state:

- The remaining time of current beacon interval is larger than $1600 \mu s$. This can be easily decided by the mobile station's local TSF timer:

$$BI - (Timer_{local} \bmod BI) \geq 1600 \mu s \quad (\text{Eq. 3.3})$$

The remaining time in current beacon interval sometimes is very short. Given that the power state transition itself require extra energy and time, the tradeoff must be determine before switch the mobile station to doze state based on the remaining time of current beacon interval. To simplify the analysis, it is assumed that the time required to switch from active state to doze state is α and vice versa. During the state switch, the energy consumption is the same as active state. Given the remaining time of current beacon interval T_r and P_a , P_s as the active state and doze state power consumption respectively, the following equation can be used to determine the state transition cost.

$$2 * \alpha * P_a + (T_r - 2 * \alpha) * P_s < T_r * P_a \quad (\text{Eq. 3.4})$$

Since P_s is normally far less than P_a , the power conservation is guaranteed as long as $T_r > 2 * \alpha$. $800 \mu s$ is considered as a conservative estimation of this value according to [67, 82]. So if the remaining time of current beacon interval is larger than $1600 \mu s$, the mobile stations will switch to doze state to conserve energy.

- Both the source and the destination mobile stations will check the scheduling information received from the beacon frame using the following procedure described in pseudo code as shown in Algorithm 3.1.

Algorithm 3.1: Algorithm for checking the schedule stack

```

1: for (each item in the schedule) do
2:   if source address = station's ID then
3:     if Number of pending packets != 0 then
4:       return (cannot return to PS state)
5:     end if
6:   end if
7:   if destination address = station's ID then
8:     if Number of pending packets != 0 then
9:       return (cannot return to PS state)
10:    end if
11:  end if
12: end for
13: return (can return to PS state)

```

Hence, mobile stations do not have to stay active for the entire beacon interval even when they have packets to transmit. Then energy efficiency can be achieved to the maximum extent.

3.3.5 Implementation of Scheduling

In our implementation of the proposed algorithm, each mobile station will piggyback the number of pending packets for current destination in each ATIM announcement packet transmitted. Furthermore the beacon will schedule the transmission in the rest of the beacon interval. As a result of such scheduling, each mobile station is aware of when it can finish its transmission of the data packets and when it can receive all the announced traffic destined for it. Since the transmissions are according to the scheduling information, each mobile station can decide, based on its local information, when it can switch to doze state. It is worth indicating that the actual state transition is only performed if it is power efficient as described in previous section.

The following describes the power state control mechanism.

- (i) The basic idea of scheduling method is to enable the mobile stations to return to the Doze state as soon as possible.

For each announced ATIM frame, there are three situations that exist if all the announced packets are transmitted.

- (a) Both the sender and receiver can switch to doze state after the transmission of all packets explicitly indicated by the number of pending packets in the ATIM announcement packet.
- (b) Only the sender or the receiver is able to switch to Doze state.
- (c) Both the sender and the receiver cannot switch to Doze state.

With respect to energy efficiency, the schedule for (a) is of the highest priority, followed by (b) and (c). Consider the following example: Suppose there are five mobile stations denoted as A, B, C, D and E. The packet announcement status is $A \rightarrow B$ (i.e. A transmits a packet to B), $A \rightarrow C$, $D \rightarrow E$ and $C \rightarrow A$. Applying the above method, The following can be obtained,

$\{A \rightarrow B\} \in (b)$, $\{A \rightarrow C, C \rightarrow A\} \in (c)$, $\{D \rightarrow E\} \in (a)$, which means that the transmission of $D \rightarrow E$ will be scheduled first because after the transmission both D and E can be switched to doze state. If $A \rightarrow B$ is scheduled to be transmitted first, then after transmission only B is able to return to doze state. If $A \rightarrow C$ or $C \rightarrow A$ is scheduled first, then after transmission none of the five mobile stations can return to doze state.

- (ii) The number of pending packets announced explicitly in the ATIM announcement frames.

Consider several simple scenarios. Suppose there are three mobile stations denoted as A, B and C. Mobile station A has announced one packet for mobile station B and mobile station B has announced two packets for mobile station C. Suppose the energy consumption for transmitting, receiving and waiting in idle for the duration of a single data packet is E_S , E_R and E_I , respectively, then the energy consumption can be estimated as follows.

Figure 3.3: A has 1 packet destined for B and B has 2 packets destined for C.

- A → B followed by B → C as shown in Figure 3.3.a.

$$E = (E_S + E_R + E_I) + 2 \times (E_S + E_R) \quad (\text{Eq. 3.5})$$

During the transmission of A → B, mobile station C has to wait in idle state until the completion of the transmission of A → B, while after the transmission of A → B, mobile station A can switch to the Doze state.

- B → C followed by A → B as shown in Figure 3.3.b.

$$E = 2 \times (E_S + E_R + E_I) + (E_S + E_R) \quad (\text{Eq. 3.6})$$

During the transmission of B → C, mobile station A has to wait in idle state until the completion of the transmission of B → C, while after the transmission of B → C, mobile station C can switch to the Doze state.

The announcement packets that have been categorized into the same priority group (as defined in 1) will be sorted by their number of pending packets. The one with a smaller number will be scheduled to transmit first.

- (iii) Multicast/Broadcast packets.

Multicast/Broadcast packets always require several mobile stations participating in the transmission. In the traditional IEEE 802.11 DCF power saving mode, if there are such

packets announced, almost all mobile stations have to stay active for the entire ATIM window. In our algorithm, the Multicast/Broadcast packets are first transmitted. After reception of these packets, mobile stations can return to doze state if the mobile station will not participate in further transmissions.

Using the schedule scheme, energy efficiency can be achieved and the network performance can be maintained.

3.3.6 Handling Special Cases

This section discusses two special cases that may occur when applying our proposed algorithm.

- (i) If there is no ATIM announcement traffic, there will be no beacon transmission when using the algorithm described in Algorithm 3.1. To solve this problem, the mobile station that has sent the beacon in the last beacon interval will transmit the beacon at the end of current ATIM window if there is no ATIM announcement traffic is overheard.
- (ii) If there is no beacon received in current ATIM window,
 - Each mobile station will contend to send a *PROBE_REQUEST* packet in the next beacon interval to the mobile station from which it received the last beacon,
 - If that mobile station is still alive, the reply of *PROBE_RESPONSE* will serve as a beacon,
 - If not, the first winning mobile station of the *PROBE_REQUEST* packets will send beacon at the end of current ATIM window using the algorithm described in section 4.1.

The *PROBE_REQUEST* and *PROBE_RESPONSE* packets will be according to the definition of IEEE 802.11 TSF.

With two additions to the existing scheme described above, the synchronization is not affected when using the proposed algorithm. Beacon is sent at the interval of *BeaconInterval* without collision. Hence it is more reliable than the contention based beacon transmission of IEEE 802.11 TSF.

3.4 Simulation of Proposed Modification of IEEE 802.11 DCF PS Mode

The performance of the proposed modification to IEEE 802.11 DCF power saving mode is evaluated using simulation programs written in C++. The simulator follows closely both the protocol details of the Power Saving Mode of 802.11 and our proposed algorithm (S-PSM) including beacon generation, ATIM window and contention based DCF access procedure.

The single-hop wireless LAN environment is simulated in which all mobile stations are within transmission range. This implies that the time synchronization is not a problem in such a scenario and active mobile stations are aware of all other transmissions. Within the ATIM window all the mobile stations should be able to work under promiscuous mode to overhear the ATIM announcement of all others.

The simulation parameters are specified in Table 3.2(a) to Table 3.2(c). Transmission errors are currently ignored in the analysis and in simulations. Thus, beacon is received without error by all the stations. Furthermore if there is no collision the data packet is also received without errors by the destination. The value of *BeaconInterval* (the length of a beacon interval) is set to 100 ms and the ATIM window is 10 ms as experimentally determined to have a good throughput and high delivery ratio.

The physical layer is modeled as the 2Mbps wireless medium as widely used in most of the IEEE 802.11 compatible devices. The physical data rate dose not significantly affect the results, since the MAC level protocol operate basically in the same way for different data rates and the modifications is only made on MAC level. The constant bit rate traffic is used with

Table 3.2: Parameters used in simulations

(a) Timing of transmission		(b) Energy consumption	
Transmission timing	Slot time	Operation mode	Energy
ACK 39 bytes	15	Idle	1.15 W
ATIM 39 bytes	15	Doze	0.045 W
Beacon 300 bytes	115	Receiving	1.4 W
Data 1024 bytes	392	Transmitting	1.65 W

(c) MAC layer parameters	
Parameters	Value
ATIM window size	10 ms
Beacon Period	100 ms
DIFS	50 μ s
SIFS	10 μ s
Slot time	10 μ s
Minimum Contention window	31
Maximum Contention window	1024

fixed length packet size of 1024 bytes. The ATIM announcement packet and ACK packet are both 39 bytes. The beacon frame is 300 bytes (to schedule at most 25 packets according to the channel capacity).

As shown in Table 3.2(b), the electrical specification and simulation parameters in [5] and [67] is utilized to model the energy consumption characteristic. The power-on transition time is also consider 800 μ s, and during the transition time, a mobile station will consume twice the power than during the idle mode [67]. At the beginning of the simulation each mobile station is assigned the same value of initial energy, which is large enough to ensure that no mobile station will run out of energy during the simulation time.

The protocols are studied with respect to four key performance metrics:

- Energy consumed per packet.

It is computed for each packet received at the destination, which accounts for the average

energy consumed by each successfully received packet. It can be described as,

$$energy_per_packet = \frac{total_energy_consumed}{total_packet_received} \quad (\text{Eq. 3.7})$$

- Packet delivery ratio.

The ratio of the number of packets received by the final destinations to the number of packets originated by sources, which is given by,

$$ratio = \frac{total_packet_received}{total_packet_generated} \quad (\text{Eq. 3.8})$$

- Average packet's end-to-end delay.

It is the average of all packets' end-to-end delay. Suppose a total of N packets have been received successfully, then the average delay can be written as,

$$average_delay = \frac{\sum_{i=0}^N (rev_time_i - gen_time_i)}{N} \quad (\text{Eq. 3.9})$$

in which rev_time_i represents the time i_{th} packet is successfully received, and gen_time_i is the generation time of i_{th} packet's.

- The ratio of average sending attempt per received packet.

$$ratio = \frac{total_send_attempt}{total_packet_received} \quad (\text{Eq. 3.10})$$

Power consumption per packet is an important issue in designing power-efficient protocols. Lower power consumption indicates more energy efficiency. The ATIM window size and the number of mobile stations are significant factors that will affect this metric. Mobile stations will always stay active during the ATIM window, which is a common awake period for all mobile stations. In addition, the collision probability is increased when more mobile stations contend

to send their data packets. Therefore, several retransmissions are expected, which increase the energy consumption directly.

Packet delivery ratio is important as it describes the loss rate that will be seen by the transport layer protocol, which in turn affects the maximum throughput that the network can support. This metric characterizes both the integrity and correctness of the protocol.

The end-to-end delay metric includes all possible delays caused by buffering latency, queuing at the interface queue, retransmission delay at the MAC and propagation and transmission time. A shorter delay can deliver a good service and has some positive effect in increasing the throughput. Actually, it does not necessarily imply a higher throughput, since delay is only measured on those successfully received packets.

To determine the actual speed of a network or connection, the goodput measurement definition may be used. For example in file transmission, the goodput corresponds to the file size (in bits) divided by the file transmission time. The goodput is the amount of useful information that is delivered per second to the application layer protocol. Dropped packets, packet retransmissions and protocol overhead are not counted. Because of that, the goodput is lower than the throughput. To simplify the calculation and analysis, the goodput is calculated according to the following equation:

The number of mobile stations in simulation is defined as n . Packet generation rate is defined as λ . Total simulation time is defined as t . Delivery ratio is defined as α . Data packet length is L .

$$goodput = \frac{n * \lambda * t * \alpha * L}{t} = n * \lambda * \alpha * L \quad (\text{Eq. 3.11})$$

The overall energy consumption of all mobile stations during a simulation instance can also be calculated in similar manner using the following equation:

The number of mobile stations in simulation is defined as n . Packet generation rate is defined as λ . Total simulation time is defined as t . Delivery ratio is defined as α . Average

energy consumption per packet is β .

$$totalenergy = n * \lambda * t * \alpha * \beta \quad (\text{Eq. 3.12})$$

One of the characteristics of the proposed algorithm is to reduce the possibility of collision in the data packet transmission phase and therefore reduce the retransmission. The ratio of average sending attempts per received packet is aimed to measure the successful sending rate. Ideally, if packet retransmission can be eliminated, the average sending attempts per received packet should be a constant number 1 since all packets can be transmitted successfully with one transmission attempt. However, transmission collision and interference often render this value greater than 1, since packets that are not successfully received have to be retransmitted by the source. Therefore, a higher average sending attempt per received packet value indicate a higher retransmission rate, which leads to higher energy consumption per packet.

The protocol is simulated under same traffic condition using the traditional PS mode of IEEE 802.11 and our algorithm. The simulation time is 50 seconds and all simulation results are the average values of 20 runs. The packet generation rate at each mobile station is 4 packets/sec and 8 packets/sec and all mobile stations have equal probability in sending packets to randomly selected destinations. The packet arrival event obeys the Poisson distribution that has exponentially distributed time between arrivals. The number of mobile stations is varied from 4 to 256 to observe the impact of performance when the network size is increased.

The ATIM window sizes of 5ms, 10ms and 20ms have been considered. There is a trade-off of the ATIM window size and other performance metric. Typically when using a larger ATIM window, more ATIM frames can be announced. Consequently there will be more contention when the data packets are transmitted, which to some extent may increase the channel utilization and decrease the packet delay. Larger ATIM window also imply longer common awake period which will lead to higher energy consumption. However, if the ATIM window is too small, there is not enough time for all mobile stations with data packets to successfully transmit their ATIM

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announcement frames. Since data packets can only be transmitted if they have already been successfully announced during ATIM window, a small ATIM window may increase the packet end-to-end delay and decrease the packet delivery ratio (if ATIM retransmission limit reaches, the corresponding data packets are dropped).

Simulation result of 5 ms ATIM window shown in Figure 3.4.a to Figure 3.9.a. Simulation results of 10 ms ATIM window are shown in Figure 3.4.b to Figure 3.9.b, and simulation result of 20 ms ATIM window are shown in Figure 3.4.c to Figure 3.9.c.

Figure 3.4: Average sending attempt as a function of the number of mobile stations

3.5 Analysis and Discussions on the Simulation Results

In the simulation, various packet generation rates is used and the ATIM window sizes to compare the performance between IEEE 802.11 PS mode and our proposed algorithm.

The ratio of average sending attempt per received packet is a very important metric that

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Figure 3.5: Delivery ratio as a function of the number of mobile stations

shows the status of channel contention of data packets. It is clear that the collision probability of ATIM packets is increased when the number of mobile stations is increased (given that all mobile stations have equal probability of sending and data packets are generated at each mobile station with the same packet arrival rate). Furthermore, the collision probability of data packets is increased when more ATIM packets have been successfully announced. Figure 3.4.b shows that this metric of IEEE 802.11 PSM reaches its local maximum when the number of mobile stations is about 64. This means that more ATIM packets are announced when mobile station number is increased from 4 to 64. With the number of mobile stations is still increasing, more mobile stations will join the contention of the ATIM packets. This results in the channel capacity becoming exhausted. A very high collision probability is also expected. This leads to the result that less ATIM packets can be announced due to the high collision probability within the ATIM window when number of mobile stations is very large. This phenomenon is

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Figure 3.6: Average packet delay as a function of the number of mobile stations

also shown in Figure 3.4.a and Figure 3.4.c, in which this turn-around point are decided by the combination of the packet generation rate and the ATIM window size. In all these figures our proposed algorithm shows its ability to reduce the collision of data packet transmission even when the number of mobile stations is significantly increased. In the proposed algorithm, the data transmission phase is scheduled by a certain centralized authority (the mobile station that overhears all the ATIM announcements and sends the beacon along with the schedule). Scheduling is based on the capacity of the channel. No more packets will be announced if they cannot be transmitted within current beacon interval. Hence the collision probability of data packets is significantly reduced.

It is worth noting that for the S-PSM case the data packet transmission attempt is not closely related to the delivery ratio. In our simulation, the traffic intensity is larger than the network capacity. Furthermore there is no delay time bound for the data packets which means that the

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Figure 3.7: Energy consumption as a function of the number of mobile stations

data packets in the sending queues of source mobile stations will not be dropped due to delay. The packet will only be dropped when the retransmission limit is reached. Unacknowledged data packets will be retransmitted up to 7 times until a positive ACK frame is received from the destination for that packet. If the queue is full, all incoming packets will be dropped. So the low delivery ratio is the result of the bandwidth constraint.

The delivery ratio is calculated by the total packets received and the total packets generated. This metric is a decreasing function with increasing number of mobile stations or packet generation rate. The channel capacity is fixed, and as more packets are generated, the less the delivery ratio after channel capacity of the data packet transmission phase is exhausted. When number of mobile stations is increased, the collision probability is also increased. Hence, the delivery ratio is decreased. As shown in Figure 3.5.a to Figure 3.5.c, in most of the cases our proposed algorithm performs almost equivalent to the traditional IEEE 802.11 or even better.

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Figure 3.8: Total system energy consumption as a function of the number of mobile stations

The goodput of the system is also calculated based on the delivery ratio. When a smaller ATIM window (eg. 5ms) is used as shown in figure 3.8.a, IEEE 802.11 can fully utilize the channel bandwidth because it uses contention based backoff mechanism for data packet transmission. So packets that have not been announced during the ATIM window might as well be transmitted. Our proposed protocol piggyback transmission schedule within beacon, which also cause extra protocol overhead. However, when a larger ATIM window (eg. 10ms or 20ms) is used, mobile stations can announce all their packets during ATIM window. In these scenarios, our protocol, which schedules the data packet transmission phase and reduce collision, will lead to higher goodput as shown in figure 3.8.b and figure 3.8.c.

In 5 ms ATIM window scenario, due to the limitation of small ATIM window size, mobile stations are often not able to successfully announce their generated packets because of packets collisions. As a result, the packets are expected to have longer end-to-end delay as illustrated

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Figure 3.9: Goodput of the system as a function of the number of mobile stations

in 3.6.a. If ATIM announcement frames exceed the retransmission limit due to severe packet collisions, the corresponding data packets will be dropped which decreases the packet delivery ratio significantly. This phenomenon has been illustrated in 3.5.a. Furthermore, since a very small ATIM window is used, the power consumption is reduced, but the performance degradation (packet end-to-end delay and delivery ratio) is unacceptable. When using 10 ms ATIM window size, the proposed algorithm maintains the network performance compared to 802.11 PSM by delivering the packets with equivalent packet average delay. When 20 ms ATIM window is used, the collision probability of the data packets transmission phase is very high and longer delay is expected because of packet retransmission. In the proposed algorithm, the data transmission phase is theoretically contention-free, since most of the data packets can be transmitted without collision. So packets delay could be significantly reduced as uniquely be noted from the simulation results.

As one of the most notable advantage of our proposed algorithm, up to 70% of the energy can be saved compared to that in 802.11 PSM as illustrated by average energy per packet figure 3.4 and total system energy consumption 3.4. This is mainly owing to the schedule announced to enable mobile stations to return to doze state after their transmission and return as soon as possible. It is worth noting that when 20 ms ATIM window is used the energy saving fraction is reduced because of the larger common awake period (ATIM window).

3.6 Conclusion

In this chapter, a modified power saving mechanism is proposed based on the power saving mode of IEEE 802.11. Simulation results show that up to 70% of the total energy can be saved compared to that in PSM of IEEE 802.11. Probability of collision is greatly reduced by a schedule that insures the data transmission to be contention free. So our proposed algorithm is more scalable when the number of mobile stations in an IBSS is increased. The proposed mechanism maintains the network performance under different conditions compared to PSM of IEEE 802.11, such as throughput, delivery ratio, average packet delay, etc. When using 20 ms ATIM windows size, up to 30% of the total energy can be saved, while at the same time the average packet delay is reduced significantly.

Chapter 4

Scheduling Mechanism for the Modified Power Saving Mode in IEEE 802.11 Distributed Coordinator Function

In IEEE 802.11 PSM specified for IBSS, mobile stations announce their pending data packets within ATIM window immediately after the reception of TSF beacon. This chapter describes several enhancements to the previously proposed modification of the IEEE 802.11 PS mode as discussed in Chapter. 3. Upon actively overhearing the traffic announcements, a mobile station can function as the centralized coordinator. It will piggyback transmission scheduling information within the beacon, which is decried extensively in chapter 3. Different traffic scheduling mechanisms are proposed in this chapter that will ensure the data packets transmission to be contention-free and minimize the total time that mobile stations have to stay in the active state. The complexity and performance of the proposed algorithms are analyzed using simulation and analytical method. The results show that the proposed algorithms improve the power efficiency and performance compared with original IEEE 802.11 protocol.

This chapter is based on the following papers:

M. H. Ye, C. T. Lau and A. B. Premkumar, " Traffic Scheduling mechanism Based on Graph Theory for Power Saving Mode of IEEE 802.11 Distributed Coordinator Function", to appear in International Journal of Ad Hoc and Ubiquitous Computing, 2007.

M. H. Ye, C. T. Lau and A. B. Premkumar, "Scheduling Mechanism for the Modified Power Saving Mode in IEEE 802.11 Distributed Coordinator Function", in *WSEAS TRANSACTIONS on COMMUNICATIONS*, Page 617-625, Issue 4, Volume 5, April 2006.

M. H. Ye, C. T. Lau and A. B. Premkumar, "Enhancing the power saving mode in IEEE 802.11 Distributor Coordinator Function using Traffic Scheduling", in *8th WSEAS International Conference on AUTOMATIC CONTROL, MODELLING and SIMULATION (ACMOS'06)*, Prague, Czech Republic, March 12-14, 2006.

4.1 Introduction

The PS mode of IEEE 802.11 protocol specified for an IBSS operates in a totally distributed manner. Mobile stations compete with each other at the beginning of each beacon interval to transmit the TSF beacon. Pending data packets are announced during ATIM window and transmitted when ATIM window finishes using DCF access procedure. The beacon and data transmissions are contention based which are expected to experience high collision probability when number of mobile stations is very large [76]. In this chapter, a novel scheduling mechanism is introduced by having a random mobile station function as the centralized scheduler which broadcasts the TSF beacon along with explicit transmission schedule at the end of each ATIM window. The scheduler organizes the data packet transmission phase in order to achieve the benefit of centralized protocol. However, all mobile stations operate under the distributed mode and no infrastructure is required. Different scheduling mechanisms are proposed and compared to observe their impact on performance. Simulation and analytical results show that the proposed methods out perform original IEEE 802.11 protocol by conserving energy of mobile stations considerably.

The rest of the chapter is organized as follows. Section 4.2 is the review of related PS mechanisms for wireless network. Different scheduling mechanisms for data packet transmissions are discussed in Section 4.3. Simulation results and performance comparison are shown in Section

4.4. The analysis and discussion are given in Section 4.5 and Section 4.6. Conclusion will be addressed in Section 4.7.

4.2 Related Works

[83] presented a Minimum Spanning Tree (MST) based topology control algorithm, called Local-MST for wireless multi-hop networks. In their algorithm, each mobile station builds its local minimum spanning tree independently and only keeps on-tree stations that are one-hop away as its neighbors in the final topology. Their protocol maintains the network connectivity while aims to minimize the stations' degree in order to reduce the MAC level contention and interference. The topology constructed by Local-MST algorithm also has a small average radius, which implies a small transmission power needed to maintain connectivity.

In [84], the authors introduce a new scheduling framework called Multiple Access Hybrid Scheduling (MAHS) that utilizes the concept of Virtual Packet which is a representation of stations' packets in the access point where actual downstream packets are also present in order to centralize the scheduling process. The scheduling function is performed solely in the access point thus enabling the use of conventional schedulers for scheduling both uplink and downlink packets (hybrid scheduling).

[78] proposed a schedule and data rate selection protocol for IEEE 802.11. In their approach, ATIM announcement frame is transmitted with the lowest data rate (1Mbps). The destination station determines the desired data rate for data packets based on the SNR of incoming ATIM frame. After the data transmission rate has been selected, each transmission is scheduled according to the data rate and the packet size. They use the shortest job first policy by setting the backoff timer of the source station according to the transmission time. As a result, the data packet with shorter transmission time will have a smaller backoff counter and thus can access the channel earlier. This scheduling protocol can not eliminate transmission collision and may deteriorate it when a small contention window is used by many transmissions with a same priority. Furthermore, the schedule can be unfair due to the shortest job first policy.

A new Enhanced DCF (EDCF) has been proposed in the forthcoming IEEE 802.11e standard [85] to enhance the QOS support for traditional IEEE 802.11 DCF by allowing different prioritized traffic classes called Access Categories (AC). The contention based channel access uses differentiated Access Category Inter Frame Space (AIFS) values, Transmission Opportunity (TXOP) Limits and Contention Windows (CW) (CW_{min} and CW_{max}) of the backoff mechanism for different priority classes. Shorter AIFS values give higher access priority, since AIFS is the constant duration for which the medium must be silent before commencing random backoff. The TXOP Limits the maximum duration that a station can use the medium for transmission. The CW parameters decide the backoff counter range, yielding higher priority to a station with smaller backoff time. These prioritization techniques enable a relative and per-class QOS in 802.11e MAC.

[86] investigates techniques for saving energy in a multiple-client scenario, where clients may be receiving either UDP or TCP data. Energy is saved by using a transparent proxy that is invisible to both clients and servers. The proxy implementation maintains separate connections to the client and server so that a large increase in transmission time is avoided. The proxy also buffers data and dynamically generates a global transmission schedule that includes all active clients.

4.3 Improving the Scheduling Mechanism

In chapter 3.3, extensive simulation results which compare the proposed protocol using categorized scheduling method with IEEE 802.11 PS mode have already been provided. In this chapter, improving the scheduling mechanism is the primary target and research focus. In this section, several scheduling mechanisms which are more efficient than the categorized scheduling method are described. These mechanisms can be further used to improve the performance of previous modification to IEEE 802.11 PS mode.

4.3.1 Construction of The Graph Based on Traffic Announcement

In the proposed algorithm, stations are in the promiscuously listening mode within the ATIM window that enables them to gather the traffic announcement information. Each ATIM announcement frame explicitly includes the following information: the addresses of the source and destination stations and number of packets the source station currently has. The traffic announcement status can be easily represented by a graph, to which existing graph theory can be applied. The stations with unique addresses are considered as vertexes in the graph. If station A has sent ATIM announcement to station B, the transmission of traffic announcement is considered equivalent to the definition in graph theory that there is an edge between vertex A and vertex B. The number of packets announced in the ATIM frame can be regarded as the weight of that specific edge. In order to construct an undirected graph, the edges with same source and destination addresses are combined together. For example, if station A has sent ATIM announcement to station B and vice versa, the two announcements are combined together into a single edge in graph with the sum of the announced packets of both ATIM frames as the weight of that edge. It is a reasonable assumption that the packets of the same source/destination pair are considered as a unit that can be scheduled as a whole, and optimization mechanisms to the MAC layer such as Implicit ACK [87] or Block ACK [88] take advantage of this characteristic. Using the assumption described above, a graph can be constructed at the end of each ATIM window. The mobile stations that have not sent or received any ATIM frame are represented in the graph as vertexes with 0 degree. In traditional IEEE 802.11 PS mode, mobile stations can switch to PS mode if they do not involve in any packet transmission after ATIM window and remain in PS state until the beginning of next beacon interval. Consequently, any vertex with 0 degree is removed from the graph after the graph construction which means the corresponding mobile station is switched to PS state. However, in traditional IEEE 802.11 PS mode, mobile stations do not switch to PS state after they finish the transmissions during the contention

period. In the previously proposed categorized scheduling algorithm [89], all announced transmissions are prioritized that enables mobile stations to finish the transmissions and switch to PS state as soon as possible. In this chapter, the same assumption is adopted as described in Algorithm 3.1. So after a successful transmission in contention period, the corresponding edge in the graph is removed. If the deletion of edges creates any vertexes with 0 degree, they are also removed from the graph which reflects the scenario that mobile stations switch to PS state after finished all their announced transmissions in current contention period.

Some definitions are addressed first as how the traffic announcement information can be transformed to the graph.

Theorem 4.1 *Assume that connection graph G consists of n vertexes and e edges, which does not include any loop. Then $A = (a_{ij})$ is a matrix of $n \times e$ members [90], in which*

$$a_{ij} = \begin{cases} 1, & \text{if } v_i \text{ is associated with } e_j; \\ 0, & \text{if } v_i \text{ is not associated with } e_j. \end{cases} \quad (\text{Eq. 4.1})$$

$A(G)$ is defined as the association matrix of G .

Figure 4.1: A sample connection graph of the transmission schedule announcement

Figure 4.1 shows an example of connection graph construction of the transmission announcements (e_1 to e_4) between 5 mobile stations (V_1 to V_5). The association matrix for connection graph in Figure 4.1 is described as following:

$$A(G) = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \quad (\text{Eq. 4.2})$$

The rows illustrate vertex v_1 to v_5 and their association with each edges. For example $A_{11} = 1$ and $A_{13} = 1$, so v_1 is associated with e_1 and e_3 . The columns illustrate edge e_1 to e_4 and their association with each vertex. For example, $A_{22} = 1$ and $A_{23} = 1$, so edge e_2 is associated with vertex v_2 and v_3 .

The association matrix have the following properties that can be use in future analysis.

- (i) In graph G , each edge is only associated with at most 2 vertexes, so in $A(G)$ there are only two non-zero elements in each column.
- (ii) The number of the non-zero elements in each row represents the degree of that specific vertex.
- (iii) An isolated vertex corresponds with an all-zero row.
- (iv) If graph G has two branches, then

$$A(G) = \begin{pmatrix} A(g_1) & 0 \\ 0 & A(g_2) \end{pmatrix} \quad (\text{Eq. 4.3})$$

This can also be generalized to the common situation, in which G is a disconnected graph with ω branches.

$$A(G) = \begin{pmatrix} A(g_1) & & & \\ & A(g_2) & & \\ & & \ddots & \\ & & & A(g_\omega) \end{pmatrix} \quad (\text{Eq. 4.4})$$

After the traffic announcement graph is obtained, the connected components of the disconnected graph can be easily identified. As shown in Figure 4.1, there are two connected components with mobile stations V_1 to V_3 belonging to component 1 and V_4 to V_5 belonging to component 2. Each connected component is relatively independent and represents the traffic announcements within a subset of mobile stations. For each component, it takes different

amount of time to finish all announced transmissions, depending on the connection pattern, the traffic intensity and the scheduling method applied. However, each connected component consists of mobile stations that only have packet announcements between each other. Owing to this unique characteristic, mobile stations in one component can switch to PS state after all announced transmissions finished without being interfered by stations in other components. So the complexity of the scheduling problem is reduced and the connected components can be considered as a minimal element for scheduling and analysis.

The task of scheduling the traffic is transformed to a two-step procedure:

- (i) Firstly, each of the connected components is assigned a weight, which is the sum of the weights of all edges within the specific component. Based on the weight of each component, all announced transmissions indicated in the component with smaller total weight can be scheduled as a group with higher priority. The component with smaller weight is expected to finish all announced transmissions in a shorter period of time that enables all mobile stations in that component to switch to PS state as soon as possible.
- (ii) Secondly, the Random Minimal Degree mechanism can be applied to schedule individual transmissions as indicated in each of the connected components. The scheduling mechanism aims to achieve a minimal total active time of all mobile stations in a component. Based on our assumptions, after each successful transmission the source or destination mobile station can decide whether it can switch to PS state by using Algorithm 3.1 to check the scheduling stack. The total active time is denoted as the sum of active time of all mobile stations in contention period, which is significantly affected by the sequence that each individual transmission is prioritized.

Using the two-step procedure, the complexity of the scheduling problem is reduced which enable us to focus on scheduling individual transmissions within each connected component. Owing to the features that each connected component is a connected and undirected simple graph, existing graph theory can be utilized to achieve a minimal total active time schedule.

4.3.2 Different scheduling mechanisms for the connected components

In the following sections, several scheduling algorithms are presented that can be applied to the connected components obtained from the traffic announcement graph as discussed in the previous section.

4.3.2.1 Random Minimal Degree Algorithm

For each connected component obtained from the graph decomposition procedure, it has the following properties:

- (i) Each component is a connected graph.
- (ii) Each component does not contain loops. (mobile stations do not transmit packets to themselves).
- (iii) Each component is a undirected graph.

Theorem 4.2 *In a connected simple graph G , there will be at least a vertex with degree 1 or an edge. When the degree-1 vertex or an edge is removed from the graph, the graph remains connected.*

Proof: If there exists a vertex v_i with degree 1, v_i is only connected with another adjacent vertex v_j . So v_i is not on any path that leads to v_j . After removing v_i , the graph remains connected.

If there does not exist any vertex with degree 1, any vertex v_i has a degree equal or larger than 2. Suppose any vertex is chosen from G and name it v_0 , a series of vertexes can be constructed by choosing any vertex v_1 from the neighbors of v_0 . Since each vertex has a minimum degree of 2, so v_1 must have a neighbor v_2 other than v_0 . The same rule applies to $v_i (i \geq 2)$ must have a neighbor other than v_{i-1} . Since there are only finite number of vertexes within G , a vertex v_k that has been chosen must be traversed for the second time. The series

$(v_0, v_1, v_2, \dots, v_k, v_{k+1}, \dots, v_k)$ is obtained, and $(v_k, v_{k+1}, \dots, v_k)$ is a cycle within G . So removing any edge from that route will not affect the connectivity of the remaining graph.

Based on the above discussion, the following conclusions can be drawn:

- (i) The vertexes with degree 1 can be removed first. These vertexes represent those mobile stations having connection with only one source or destination and after the transmission they can switch to PS state.
- (ii) If no vertex satisfies the above criteria, there exist edges that can be removed without affecting the graph connectivity.
- (iii) Repeatedly removing those edges will create vertexes with degree 1, which can satisfy the first criteria.

According to the analysis above, the RMD Algorithm is proposed to schedule the transmissions within a connected component. The basic idea for the RMD Algorithm is to schedule the transmissions of mobile stations that have minimal connections with higher priority. As depicted in the graph scenario, the procedures are described as following:

- (i) First, find a vertex with minimal degree. If several vertexes have same degree, the sums of weight of all edges associated with those vertexes are calculated respectively and the vertex with minimal sum of weight is chosen. If several vertexes still have the same sum of weight, then a random vertex is chosen among them.
- (ii) The incident edges of the chosen vertex are selected as candidates for removal (corresponding to the scenario that the transmission is scheduled). The edge with minimal weight is given higher priority. If several edges have the same weight, then a random edge is chosen among them.

- (iii) The chosen edge is removed from the graph. If the removal of the edge creates any vertex with 0 degree, then the vertexes are also removed (mobile stations finish all announced transmissions and return to PS state).
- (iv) The whole procedures will be executed from the beginning on the reduced graph if an edge or a vertex is removed.

4.3.2.2 Scheduling with Minimal Spanning Tree Algorithm

For each of the connected components, a MST can be generated. The MST contains the minimal number of edges that connect all vertexes and the sum of weight is minimal. Using the MST, the edges within the connected component can be separated into two categories, the edges within the MST and the edges within the graph but not included in the MST. The MST has the following characteristics which can be utilized in the scheduling decision.

- (i) All vertexes with their degree equal to 1 will have their incident edges included in the MST.
- (ii) The MST contains the edges that connect all vertexes with minimal total weight. So edges with smaller weight are likely to be chosen.
- (iii) The MST contains all the vertexes. In perspective of traffic scheduling, all mobile stations have equal priority to be scheduled. Scheduling the transmissions indicated in the MST can achieve a fair schedule for all mobile stations.

So in the MST algorithm, the transmissions as indicated in the MST are scheduled with higher priority.

Theorem 4.3 *Every connected graph G contains a normal spanning tree T , with any specific vertex as its root.*

Proof: If G is a connected graph without a circuit, then obviously G is a normal spanning tree itself. If there exists one circuit in G , then any edge can be deleted from that circuit and the graph is still connected. The remaining graph G' is a normal spanning. If there exists multiple circuits within G , then the previous procedure is repeated until a normal spanning tree is obtained.

Algorithm 4.1 is a pseudo code to find a minimal cost spanning tree in G [90].

Algorithm 4.1: Minimal Cost Spanning Tree Algorithm

```

1: Denote  $T$  as the group of the edges that have been chosen.
2: Set  $T = \phi$ 
3: Denote  $E$  as the group of all the edges within  $G$ 
4: while ( $E \neq \phi$ ) && ( $|T| \neq n - 1$ ) do
5:   Find  $(u, v)$  as the minimal cost edge in  $E$ 
6:    $E = E - (u, v)$  {remove edge  $(u, v)$  from  $E$ }
7:   if (adding  $(u, v)$  to  $T$  does not create any circuit) then
8:     add  $(u, v)$  to  $T$ 
9:   end if
10: end while

```

After the MST is generated, the transmissions indicated in the MST are scheduled to be transmitted first with higher priority. After all transmission indicated in the MST finished, the transmissions indicated in the graph but not included in the MST are then scheduled. It should be noted that all transmissions are prioritized by their weights. Under the same condition, the transmissions with smaller weights are scheduled with higher priority.

Furthermore, an enhanced MST algorithm is proposed by combining the Minimal Spanning Tree Algorithm and the Random Minimal Degree Algorithm as described in the previous section. It operates in the following procedures.

- (i) Generate the MST of the connected component.
- (ii) Schedule the transmission indicated in the MST by using the Random Minimal Degree Algorithm.

- (iii) schedule the transmission indicated in the graph but not included in the MST by using the Random Minimal Degree Algorithm.

The combined protocol takes advantage of the two proposed algorithms (RMD and MST), which is capable of providing a more energy efficient schedule and achieving fairness among different mobile stations.

4.3.2.3 Using the method of Knapsack Problem to schedule the transmission

The ultimate objective of a transmission schedule is to minimize the total active time of all mobile stations. Each individually announced transmission is prioritized by the factors such as the number of announced packets and whether the sender or receiver can switch to PS state. The scheduling problem is very similar to the traditional Knapsack Problem. In traditional Knapsack Problem, there are different items and a limit (total weight or size). The items have a certain cost (e.g. size or weight) and a certain value (e.g. resale value) associated with them. The limit is a cost-limit (e.g. size limit or weight limit). The goal is to find the combination of items that is below the given cost-limit but gives the best value.

Based on the above observation, a Knapsack scheduling algorithm is proposed. In IEEE 802.11 PS mode, transmission time is divided into series of beacon interval by periodical sending time synchronization frame. So the actual data packet transmission time (the contention period) is bounded by the length of the beacon interval and the ATIM window size and their relationship can be describe in the following equation.

$$TransmissionTime = BeaconInterval - ATIMwindowSize \quad (Eq. 4.5)$$

So the number of packets that can be transmitted has an upper bound which is restricted by the length of the contention period. This upper bound is equivalent to the cost-limit definition in the Knapsack Problem. Each individually announced transmission can be regarded as different items and the number of packets announced is treated as the weight of the item in the Knapsack

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Problem. Since the schedule aims at minimizing the total active time, different transmissions can be assigned with different values with respect to the expected active time of both send and receiver. The two major factors that affect the expected active time of send and receiver after a successful transmission are the vertex degree of the two stations and the number of packets announced. The following equation is used to calculate the value of a transmission.

$$value = \frac{normalize\ factor}{weight \times (degree_{sender} + degree_{receiver})} \quad (\text{Eq. 4.6})$$

The transmissions with higher value tend to be finished in shorter period of time and enable sender or receiver to switch to PS state. Based on the above notation, the scheduling problem is transformed to a classic Knapsack problem. The following is the pseudo code to solve the Knapsack problem using greedy method. However, in our algorithm, a modified version is used with optimization and capable of handling floating point value and large number of items with same weight.

Denote the following abbreviation:

W[i]: Weight of the items

V[i]: Value of the items

Algorithm 4.2: Algorithm to solve knapsack problem with n items

```

1: int F(int i, int y) {
2:   if (i == n) then
3:     return (y < W[n]) ? 0 : V[n]
4:   end if
5:   if (y < W[i]) then
6:     return F(i+1,y)
7:   end if
8:   return max(F(i+1,y), F(i+1,y-W[i]) + V[i])

```

By using the solution to the classic Knapsack problem, the scheduling problem can be systematically solved. Although this method can be computationally intensive if the number of items is very large, the result can still be used as a good reference to compare with other methods.

4.4 Simulation Results

In order to compare the proposed protocols, a simulation program is developed using C++ that implements the proposed scheduling mechanism as well as the previously proposed categorized scheduling method and IEEE 802.11 PS mode. The simulation program utilizes the well-known C++ Boost Graph Library [91] for all graph operations. The simulation parameters is the same as comprehensively described in Chapter 3 in Table 3.2(a), Table 3.2(b) and Table 3.2(c).

In the simulation program, the number of mobile stations as well as the traffic intensity are varied in order to observe their impact on the power efficiency. In our proposed protocols, mobile stations periodically switch between the PS state and the active state. All mobile stations switch to active state at the beginning of each beacon interval and remain active for the duration of ATIM window. Mobile stations can switch to power saving state after the ATIM window if they are not involved in any announced transmissions or during the contention period of the beacon interval if they finish all their announced transmissions. The cumulated time that all mobile stations stay in active state during the entire contention period is denoted as the total active time. Since mobile stations randomly generate their packets with constant rate and different scheduling mechanisms are applied to optimize the same traffic announcement status, a smaller total active time indicates higher energy saving of all mobile stations.

4.2.a: Minimal connected

4.2.b: Fully connected

Figure 4.2: Comparison of total active time of mobile stations in a connected component

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Figure 4.2.a to Figure 4.3.b shows the simulation results by varying the size of the connected components. The simulations are designed to illustrate the characteristics and performance of different scheduling algorithm separately. In the simulation, a connected graph is randomly generated with given number of mobile stations, which represents the connected components after the whole traffic announcement graph is successfully decomposed as described in previous section. The traffic conditions are varied by control the number of ATIM announcements (corresponding to the number of edges in generated graph). Suppose there are N stations (corresponding to N vertexes in the graph), a minimal connected component only has $N - 1$ edges and a fully connected component has $\frac{N*(N-1)}{2}$ edges. A component with low connectivity has the number of edges within the range of $(N - 1, \frac{N*(N-1)}{4})$. A component with high connectivity has the number of edges within the range of $(\frac{N*(N-1)}{4}, \frac{N*(N-1)}{2})$. This simulation calculates the cumulated active time of all mobile stations in a connected component during a beacon period when different scheduling mechanisms are used. The values showed in figures are average results of 100 beacon intervals. A smaller total active time indicates a higher energy saving for a group of mobile stations. The MST + RMD algorithm is a combined method, in which a MST is generated for the connected component and the Random Minimal Degree algorithm is applied to the MST and to the rest of the graph. This method performs about

4.3.a: Randomly generated with low connectivity

4.3.b: Randomly generated with high connectivity

Figure 4.3: Comparison of total active time of mobile stations in a connected component

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10% better than our previously used categorizing method.

Figure 4.4.a to Figure 4.4.c shows the simulation results by varying the number of mobile stations and applying the proposed algorithms to the traffic announcement graph. The simulations are designed to illustrate the characteristics and performance of different scheduling algorithms separately. In the simulation, a graph is randomly generated with given number of mobile stations, which represents the traffic announcement status after ATIM window. The program simulates the procedures including random traffic generation and announcement in ATIM window, construction of the traffic announcement graph based on the transmitted ATIM frames, power state transition after ATIM window or after successful packet transmission if applicable and traffic scheduling using the proposed algorithms. In order to show the stability of the proposed algorithms, the traffic intensity is manipulated by varying the number of

4.4.a: Low traffic condition

4.4.b: Medium traffic condition

4.4.c: High traffic condition

Figure 4.4: Comparison of total active time of mobile stations in whole graph

ATIM announcements during each beacon interval. Suppose there are N stations, the low traffic condition represents the scenario that the number of ATIM announcements mobile stations generated during each ATIM window is uniformly distributed within the range of $[0, \frac{N}{2}]$. The medium and high traffic condition represent the scenario that the number of generated ATIM announcements is within the range of $(\frac{N}{2}, N)$ and $(N, \frac{3N}{2})$, respectively. All proposed algorithms have significant performance gains over the categorized method, especially when the number of mobile stations is very large and the traffic load is high. The MST + RMD algorithm performs better than the categorized method by reducing the total active time for about 40%.

4.5 Algorithm Complexity

In this section, a brief analysis of the complexity of our proposed algorithms is given, which might be used as criteria for selecting the proper algorithm for actual implementation.

4.5.1 The Categorizing Method

In our categorized scheduling method, the station that has transmitted the first ATIM announcement frame in current beacon interval is responsible to overhear the traffic announcements during the ATIM window. Based on the overheard information, the station calculate a proper schedule to control the traffic during the contention period by piggyback an explicit transmission order in the beacon frame and broadcast it to all other stations. Other stations follow the transmission order which makes data packets transmission contention-free. Assuming that the traffic announcements during ATIM window are collected, our program will operate as following:

- (i) Sort all ATIM announcement frames with their metrics (number of packets announced) in ascending order.
- (ii) Find an ATIM announcement frame with minimal metric.

- (iii) Find whether the sender or receiver indicated in the ATIM announcement frame has traffic to other mobile stations by searching all rest ATIM announcement frames.
- (iv) If both the sender and receiver do not have packets for other mobile stations, the specific transmission is categorized into the first transmission category.
- (v) If the sender or the receiver is involved in packet transmissions as indicated in other ATIM announcement frames, the specific transmission is categorized into the second transmission category.
- (vi) Otherwise, the specific transmission is categorized into the third transmission category, which means both sender and receiver cannot switch to PS state after the transmission.

In simulations, the commonly known heapsort algorithm is used for the first step with the time complexity $O(k \log(k))$, where k is the number of ATIM announcement frames. It is obvious that the maximum number of ATIM announcements between n mobile stations is $\frac{n(n-1)}{2}$ (ATIM frames with same source and destination addresses are combined as described previously). So the time complexity of the first step is $O(n^2 \log(n))$. In the second and third steps, the time complexity is $O(kn)$ since the connection status of each mobile station has to be calculated by recursively searching all ATIM announcement frames. So the total time complexity of the categorized scheduling method is $O(n^2 \log(n) + n^3)$.

4.5.2 The RMD Algorithm

In the RMD Algorithm, the graph is first decomposed into connected components. The time complexity for the graph decomposition is known to be $O(V+E)$, where V and E are the number of vertexes and edges, respectively. It is also known that the maximum number of edges in a simple undirected graph without loop is $\frac{n(n-1)}{2}$. So the time complexity of graph decomposition is $O(n^2)$. The transmissions indicated in the connected component are consequently scheduled using the RMD Algorithm by sorting all vertexes with their degrees in ascending order. The time

complexity of sorting the vertexes is $O(n \log(n))$. So the time complexity of the RMD algorithm can be represented as $O(n^2 + n \log(n))$. According to the above analysis, the RMD algorithm is easy to be implemented and consumes less computational power than the categorized scheduling method.

4.5.3 The Minimal Spanning Tree Algorithm

In our simulation, Minimal Spanning Tree algorithm proposed by V. Kevin [92] is used to construct the MST of a given graph. The benefit of this method is that the procedure will generate a minimal spanning forest containing the minimal spanning trees of the disjoint components joined together by edges of length infinity if the graph is not connected. The time complexity of this algorithm is $O(n^2)$. Our algorithm first generated the minimal spanning tree, then randomly choose the edges from the spanning tree for scheduling. If there are still edges left, they will also be chosen randomly for scheduling. So the time complexity is also $O(n^2)$.

4.5.4 The Minimal Spanning Tree + Minimal Degree Algorithm

In this algorithm, the MST of the connected component is generated first. The transmissions indicated in the MST is scheduled with higher priority by using the Random Minimal Degree Algorithm. The remaining transmissions indicated in the graph but not included in the MST is consequently scheduled by using the Random Minimal Degree Algorithm too. So the time complexity is $O(n^2 + n \times \log(n))$.

4.5.5 Knapsack Algorithm

In this algorithm, a recursive searching and greedy approach is used as described previously to construct the knapsack and the schedule is prioritized by the value that is associated with the specific edge. So the time complexity is $O(2^k)$ [93], k is the number of edges. Considering a complete directed graph with $2n \times (n - 2)$ edges, the algorithm complexity is $O(2^{2 \times n^2})$.

4.6 Numerical Results of the Algorithms

In this section, the proposed algorithms are analyzed and the upper-bound and lower-bound of the algorithm efficiency is defined.

4.6.1 Numerical Results of The Categorized Scheduling Method

In the categorized scheduling method, all transmission are prioritized into three transmission categories as described previously. Assuming that the categorizing procedures for a graph with k edges and n vertexes are finished successfully, the following sequence of edges $(e_i, 1 \leq i \leq k)$ for the graph can be obtained and they are in ascending order of the metric $(M_i, 1 \leq i \leq k)$ in each category. For simplicity reason, it is assumed that transmission and reception of a packet occupy the wireless medium for one slot time.

$$\underbrace{e_1, e_2, \dots, e_i}_{category1} \underbrace{e_{i+1}, \dots, e_j}_{category2} \underbrace{e_{j+1}, \dots, e_k}_{category3} \quad (\text{Eq. 4.7})$$

- In the graph, there are i edges belonging to the first category. According to the definition of the category 1, each vertex in this category has the degree of 1. This simply means that there are i independent edges in this category. So there are $2 * i$ vertexes (mobile stations) in this category. Since in this category both the source and destination mobile stations can return to PS state after a transmission, the following equation can be used to describe the total active time (in unit of slot time) of the first category transmission.

$$Active_{cat1} = \sum_{m=0}^{i-1} (n - 2 * m) * M_{m+1} \quad (\text{Eq. 4.8})$$

- There are $j - i$ edges in the graph belonging to the second category. According to the definition of the second category, each edge has one vertex with degree equal to 1 and another vertex with degree greater than 1. Considering the extreme case that all edges have a common vertex, there are at least $(j - i) + 1$ vertexes in this category. Considering another extreme case that there are independent pairs of edges with one common vertex

in each pair (two edges share one common vertex), there are at most v ($v = \lceil \frac{3*(j-i)}{2} \rceil$) vertexes in this category. According to the definition, after each individual transmission in category 2, the source or the destination mobile station is able to return to the PS state. So in the first extreme case at least $j - i$ mobile stations can return to PS state after the second category transmission. For the second extreme case, at most v mobile stations in category 2 can switch to PS state. The following equations can be used to describe the lower bound and upper bound of the total active time of the second category transmission.

To consider the lower bound, the following equation can be obtained:

$$Active_{cat2}^{lower} = \sum_{m=0}^{j-i-1} (n - 2 * i - m * \frac{v-2}{j-i-1}) * M_{m+i+1} \quad (\text{Eq. 4.9})$$

To consider the upper bound, the following equation can be obtained:

$$Active_{cat2}^{upper} = \sum_{m=0}^{j-i-1} (n - 2 * i - m) * M_{m+i+1} \quad (\text{Eq. 4.10})$$

- After the third category transmissions, all stations can switch to PS state. The following equations can be used to describe the upper bound and lower bound of total active time of the third category transmission.

To consider the lower bound, there are $(n - 2 * i - v)$ mobile stations remain active in third category. The following equation can be obtained:

$$Active_{cat3}^{lower} = \sum_{m=0}^{k-j-1} (n - 2 * i - v - m * \frac{n-2*i-v}{k-j-1}) * M_{m+j+1} \quad (\text{Eq. 4.11})$$

To consider the upper bound, there are $(n - i - j)$ mobile stations remain active in third category. The following equation can be obtained:

$$Active_{cat3}^{upper} = \sum_{m=0}^{k-j-1} (n - i - j - m * \frac{n-i-j}{k-j-1}) * M_{m+j+1} \quad (\text{Eq. 4.12})$$

The lower bound of the categorizing method can be described using the following equation:

$$Active_{cat}^{lower} = Active_{cat1} + Active_{cat2}^{lower} + Active_{cat3}^{lower} \quad (\text{Eq. 4.13})$$

The upper bound of the categorizing method can be described using the following equation:

$$Active_{cat}^{upper} = Active_{cat1} + Active_{cat2}^{upper} + Active_{cat3}^{upper} \quad (\text{Eq. 4.14})$$

4.6.2 Numerical Results of the RMD Algorithm

The RMD algorithm can be analyzed using the theory of MST. Since the MST contains all vertexes in a connected graph and the edges that connect all vertexes with minimal total weight, the vertexes and corresponding edges chosen by the RMD algorithm should be included in the MST of the connected graph. The RMD algorithm performs similar to the scenario when all edges in MST are scheduled first followed by the edges in the graph but not in the MST. Using the MST for analysis can simplify the problem while still provide a close estimation. In the RMD algorithm, after removing an edge or vertex from the graph, the next edge is chosen from the reduced graph. However, using MST based analysis, the MST is constructed based on the original graph only once.

Assuming that the construction procedure of the MST for a graph with k edges and n vertexes is finished successfully, the following sequence of edges for the graph can be obtained:

$$\underbrace{e_1, e_2, \dots, e_{n-1}}_{MST}, \underbrace{e_n, \dots, e_k}_{Other} \quad (\text{Eq. 4.15})$$

The first group of edges belongs to the MST. For a given connected graph with n vertexes, there are $n - 1$ edges in the MST and $k - n + 1$ other edges that are in the graph but not in the MST. In our RMD algorithm, the edges from the MST are normally chosen to be scheduled first followed by the choosing of edges from the rest of the graph. The worst case scenario (consumes most energy) is that the $k - n + 1$ edges involve all n vertexes, so no station can switch to PS state after the transmissions indicated in the MST are finished. The best case

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scenario (consumes least energy) is that the other $k - n + 1$ edges involve minimal number of vertexes, while the corresponding stations that are not involved can switch to PS state after transmissions indicated in the MST are finished.

For the best case scenario, the minimal number of vertexes (v) that are involved in all other edges is calculated first.

$$k - n + 1 = \frac{v * (v - 1)}{2}; \quad (\text{Eq. 4.16})$$

Solve this equation with k and n as the known variable, the expression for v (the minimal number of stations that still can not switch to PS state) can be obtained:

$$v = \lceil \frac{1 + \sqrt{1 + 8 * (k - n + 1)}}{2} \rceil; \quad (\text{Eq. 4.17})$$

So after the transmissions indicated in the MST finished, the number of stations that can switch to PS state is $n - v$. The actual time that each of the stations switches to PS state is not known, since the transmission is randomly chosen and the traffic condition is also randomly announced. An average function is therefore used to have fairly precise estimation of the active time of each station.

$$Active_{mst}^{lower} = \sum_{m=0}^{n-2} (n - m * \frac{n - v}{n - 2}) * M_{m+1} \quad (\text{Eq. 4.18})$$

For the worst case scenario, after the transmissions indicated in the MST finished, no stations can switch to PS state.

$$Active_{mst}^{upper} = \sum_{m=0}^{n-2} n * M_{m+1} \quad (\text{Eq. 4.19})$$

After the transmission indicated in the MST finished, the rest of the transmissions indicated in the graph can be scheduled. However, there are still v and n stations remaining in the active state in the best and worst case scenario respectively. Considering using an average function, the following equation can be used to describe the total active time. For the best case scenario:

$$Active_{other}^{lower} = \sum_{m=0}^{k-n} (v - m * \frac{v}{k - n}) * M_{m+n} \quad (\text{Eq. 4.20})$$

For the worst case scenario:

$$Active_{other}^{upper} = \sum_{m=0}^{k-n} (n - m * \frac{n}{k-n}) * M_{m+n} \quad (\text{Eq. 4.21})$$

The lower bound of the RMD algorithm can be described using the following equation:

$$Active_{RMD}^{lower} = Active_{mst}^{lower} + Active_{other}^{lower} \quad (\text{Eq. 4.22})$$

The upper bound of the RMD algorithm can be described using the following equation:

$$Active_{RMD}^{upper} = Active_{mst}^{upper} + Active_{other}^{upper} \quad (\text{Eq. 4.23})$$

4.6.3 Minimal Spanning Tree Algorithm + Random Minimal Degree Algorithm

This method should be very close to the lower-bound of the RMD algorithm that have been analyzed in the previous section, which can be described in the following equation:

$$Active_{MST+RMD}^{lower} = \sum_{m=0}^{n-2} (n - m * \frac{n-v}{n-2}) * M_{m+1} + \sum_{m=0}^{k-n} (v - m * \frac{v}{k-n}) * M_{m+n} \quad (\text{Eq. 4.24})$$

$$Active_{MST+RMD}^{upper} = \sum_{m=0}^{n-2} n * M_{m+1} + \sum_{m=0}^{k-n} (n - m * \frac{n}{k-n}) * M_{m+n} \quad (\text{Eq. 4.25})$$

In Eq. 4.24 and Eq. 4.25, v is defined in Eq. 4.17 previously.

4.6.4 Knapsack Algorithm

In our proposed Knapsack algorithm for scheduling, the actual number of packets that can be transmitted during the beacon period is used as the knapsack size. The number of packets that have announced between any two mobile stations is used as the weight. The estimation of the value of a specific transmission is calculated by using the weight and the sum of the degree of both sender and receiver. The edges with their values in descending order are chosen for scheduling. The knapsack algorithm should have similar performance compared with the

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MST algorithm. In the knapsack algorithm the transmission with the combination of minimal number of packets announced and minimal total degree are chosen for scheduling first. Such edges are often chosen in the MST, since in the MST algorithm the chosen edges satisfied the following criteria:

- (i) It first chooses the edge with minimal degree.
- (ii) The newly added edge does not create any circuits in the graph.
- (iii) Any edges with a vertex degree equal to 1 is definitely chosen.

So the probability that an edge is chosen in the MST and the beginning of knapsack are very high.

The numerical results obtained from the traffic schedule using the categorized method and the RMD algorithm are shown in Figure 4.5.a to Figure 4.7.b. For simplicity of the analysis, it is assumed that all edges have the same metric equal to 1, which means each station announce same number of packets in ATIM announcement frame. Furthermore, our analysis is based on the known announcement status of all traffic between mobile stations. In order to achieve this, for a given number of mobile stations in the system, traffic are randomly generated between them with different traffic conditions. The number of mobile stations in each traffic category

4.5.a: The Categorized Algorithm

4.5.b: The Minimal Spanning Tree Algorithm

Figure 4.5: Lower and higher bound as a function of the number of node for low traffic condition

(used in the analysis of categorized method) and in the MST (used in the analysis of RMD algorithm) can be obtained through the randomly generated traffic information. Therefore, the expected total active time of all mobile stations can be calculated using the equations derived in previous section to get the lower bound and higher bound of total active time. The simulation results showed in the figures are the average of values of 100 simulation runs.

4.7 Conclusion

This chapter proposes a modifications to IEEE 802.11 PS mode by sending the TSF beacon at the end of each ATIM window. Upon actively overhearing the traffic announcements within ATIM window, the packet transmission properly scheduled by piggyback transmission arrangement information within the beacon. Several traffic scheduling mechanisms are proposed, which provide a fair and power efficient service for all mobile stations. The scheduling information will ensure the data packets transmission to be contention-free and minimize the total time that mobile stations have to stay in the active state. The complexity and performance of the proposed algorithms are analyzed using simulation method and analytical model. The results show that the proposed algorithms performs better in different aspects compared with original IEEE 802.11 protocol.

4.6.a: The Categorized Algorithm

4.6.b: The Minimal Spanning Tree Algorithm

Figure 4.6: Lower and higher bound as a function of the number of node for medium traffic condition

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4.7.a: The Categorized Algorithm

4.7.b: The Minimal Spanning Tree Algorithm

Figure 4.7: Lower and higher bound as a function of the number of node for high traffic condition

Chapter 5

A Power Efficient Access Point Operation for Infrastructure Basic Service Set in IEEE 802.11 MAC Protocol

Infrastructure based wireless LAN technology has been widely used in today's personal communication environment. Power efficiency and battery management have been the center of attention in the design of hand-held devices with wireless LAN capability [94]. In this chapter, a hybrid protocol is proposed which intelligently chooses the AP assisted DCF and enhanced PCF transmission mechanism of IEEE 802.11 protocol in an infrastructure based wireless LAN environment. RSSI is used to determine the trade-off between direct mobile-to-mobile transmission and transmission routed by AP. Based on the estimation, mobile stations can efficiently communicate directly instead of being routed by AP if they are in the vicinity of each other. This protocol is also further extended by utilizing the historical end-to-end delay information to decide the waking up time of mobile stations. Simulation results show that using the proposed protocol energy consumption of mobile devices can be reduced at the cost of slightly longer end-to-end packet delay compared to traditional IEEE 802.11 PCF protocol. However, in a non-time critical environment, this option can significantly prolong the operation time of mobile devices.

This chapter is based on the following papers:

Ye Ming Hua, Lau Chiew Tong, and Benjamin Premkumar, A Power-Efficient Access Point Operation for Infrastructure Basic Service Set in IEEE 802.11 MAC Protocol, EURASIP Journal on Wireless Communications and Networking, vol. 2006, Article ID 63728, 14 pages, 2006. doi:10.1155/WCN/2006/63728

M. H. Ye, C. T. Lau and A. B. Premkumar, "Power Efficient MAC Protocol Through Intelligent Transmission Mechanism Selection for IEEE 802.11 Based Infrastructure Basic Service Set", in *WSEAS TRANSACTIONS on COMMUNICATIONS*, Page 922-930, Issue 5, Volume 5, May 2006.

M. H. Ye, C. T. Lau and A. B. Premkumar, "Enhanced Point Coordinator Function in IEEE 802.11 MAC Protocol for Infrastructure Basic Service Set", in *5th WSEAS International Conference on APPLIED COMPUTER SCIENCE (ACOS '06)*, Hang Zhou, China, April 16-18, 2006.

5.1 Introduction

In an infrastructure based wireless LAN communication scenario such as airports hot-spots and internet cafes, users can use their computing facilities to get internet access without the constraint of network cable. The communication is mainly between the AP and mobile stations. In other scenarios such as the lecture theater or conference hall where most users tend to exchange information between each other, the traffic is likely to be between different mobile stations. IEEE 802.11 specified the PCF mode to provide contention free access which can guaranty a fair and predictable service for mobile stations. The PCF operation mode is aimed to be used for the infrastructure Basic Service Set (BSS) that requires the presence of an AP which acts as a centralized coordinator for traffic control of all the mobile stations within its coverage area. Instead of communicating with each other directly using DCF protocol, all traffic of mobile stations must be routed through the AP in infrastructure BSS. AP can also act as

the gateway between the local mobile network and the external network such as Internet. Our analysis shows that using IEEE 802.11 PCF protocol for the infrastructure network cannot achieve an optimal performance in such environments.

In this chapter, a modification to the PCF operation of IEEE 802.11 protocol is proposed that reduces the energy consumption and increases the throughput. The proposed protocol improves the mobile-to-mobile traffic in the infrastructure network using DCF transmission mechanism assisted by the AP. The protocol behavior and performance of traditional IEEE 802.11 PCF is analyzed first especially in an environment where traffic is mostly mobile to mobile. The improved PCF operation is introduced which adaptively selects between PCF and AP assisted DCF transmission mechanism based on RSSI information of mobile stations for different traffic types. A two-phase polling mechanism is proposed. The first polling phase is utilized for traffic information collection and downlink traffic. The AP will poll all eligible stations in a round-robin fashion. The contention-free period ends when AP sends the control frame of subtype CF-end, which piggybacks the explicitly transmission scheduling information for DCF transmission between mobile stations [89] of the packets that have been announced in the first polling phase and have not been transmitted during the second polling phase. An AP assisted retransmission mechanism is also proposed. Mobile stations can pass their unsuccessfully transmitted packets in direct transmission phase to AP during next polling phase and AP can help to retransmit packets to the destination mobile stations. Furthermore, historical delay information and the request sending time is utilized to predict the end-to-end delay, which is then utilized to decide the waking up time of mobile stations efficiently. Stations will not wake up earlier from their power saving state than the expect arrival time of the reply packets in a client-server based communication scenario. Our proposed protocol operates in a hybrid mode by taking advantage of the capability of AP and the flexibility of AP assisted DCF operation that is capable of providing a service with reduced power consumption and increased throughput.

The rest of the chapter is organized as follows. Section 2 briefly reviews the power saving mechanism specified in IEEE 802.11 standard and related works that improve the AP operation. Section 3 presents the proposed enhancements to IEEE 802.11 PCF protocol to achieve energy efficiency and throughput improvement. Section 4 describes the simulation model and results which show the advantage of the proposed algorithm. Section 5 concludes the chapter.

5.2 Related Works

In [95], the authors propose an adaptive control algorithm to keep the aggregate throughput of AP close to the best capacity of both DCF and PCF mode based on various traffic requests. They use throughput as the feedback indicator to determine whether current dominant access method fits the traffic pattern. The throughput in PCF mode and in DCF mode are measured periodically using an estimation algorithm according to current traffic condition. Based on this information, the percentage of CFP duration within a super-frame is actively controlled by AP to achieve an optimal aggregate throughput.

In [96], the authors propose a novel relay-enabled PCF (rPCF) to exploit the multi-rate capability of IEEE 802.11 WLANs. Based on the channel condition, rPCF may use multi-hop data transmission through MAC layer relay to improve the system performance. An intermediate relay node is used to forward traffic instead of direct transmission if the links from the sender to the relay node and from the relay node to the receiver can support higher data rate than direct link. In this protocol, the AP has to monitor and maintain the connection status (eg. reachability, connection data rate and congestion level etc.) between all mobile stations and this can become a large overhead. The information can also get outdated since mobile stations move constantly. Furthermore since the two-hop relay transmission is used, it may increase the collision probability and the packet error rate.

The authors further introduce a rDCF protocol in [97] which extend the MAC layer relay idea to DCF operation. The problem is that the node that helps to forward the packets

consumes extra energy, which may not be power efficient. Although the higher transmission data rate through the intermediate node may decrease the transmission time which reduces energy required for sending, the extra binary exponential backoff time for two transmissions through the relaying node as well as the control overhead (eg. RTS/CTS, ACK etc.) may forfeit the energy saving.

In the forthcoming IEEE 802.11e protocol [85], a Direct Link Protocol (DLP) is proposed. Direct link refers to the ability to exchange data directly between two stations in the network, without being routed through the AP. The traditional 802.11 MAC specifies that stations can only communicate with APs in an infrastructure BSS. This is to ensure that communication is possible between all stations, even if they are out of range to each other. But this reduces the available bandwidth for station-to-station communication by possibly more than one half. DLP in 802.11e provides a mechanism to allow direct station-to-station communication in the case where the stations are in range of each other. In our proposed approaches, the tradeoff between a direct link transmission and the AP routed transmission is determined based on the RSSI information of mobile stations. A direct transmission is used only if it conserves energy than a routed transmission. An AP-assisted retransmission mechanism is also proposed that passes the unsuccessfully delivered packets to AP to conserve energy and reduce channel collision possibility.

5.3 Enhanced PCF Operation of Access Point

In this section, detailed description as how the traditional IEEE 802.11 PCF protocol can be modified to achieve a better performance will be given. The original IEEE 802.11 is analyzed to show that PCF is not suitable for the environment where most traffic is between mobile stations in an infrastructure BSS. Then our improved PCF operation is introduced which is a hybrid protocol using AP assisted DCF operation for mobile-to-mobile traffic in an infrastructure based wireless LAN environment. Experiments of signal strength measurement is also conducted. It

shows that the overheard signal strength information, which is used as an important metric in our protocol, is sufficient to determine the trade-off between direct and routed transmission. Furthermore, an end-to-end delay estimation method is introduced of traffic between mobile stations and a remote server attached to AP through wired link. The delay estimation is used to efficiently determine the waking up time of mobile stations, which reduces unnecessary energy consumption when mobile stations stay in idle state without transmitting or receiving any data. Since the upper layer protocol may significantly affect the delay, historical delay information is used for our estimation. Furthermore, only the stations that are expecting their reply packets in current contention-free period stay in active state, which shortens the length of the polling list of AP. This also reduces the end-to-end packet delay and increase the throughput of traffic between mobile stations and AP.

5.3.1 Problem Analysis of IEEE 802.11 PCF

IEEE 802.11 PCF mode is a centralized polling scheme, which uses AP as a coordinator for all communications within its coverage. The benefit of using the AP is obvious: it will guarantee a contention-free transmission period through the centralized polling. However it also has the following drawbacks in an infrastructure BSS:

- (i) During each CFP, the AP shall issue polls to a subset of the stations on the polling list in order by ascending Association Identifier (AID) value. During the CFP, if all Contention Free (CF) frames have been delivered and all STAs on the polling list have been polled, the AP may generate one or more CF-Polls to any stations on the polling list. However, this is often not possible when number of mobile stations is large and the traffic intensity is high. If it is assumed that mobile stations can only be polled once during each beacon interval, the average delay between two consecutive transmissions of a mobile station is the length of the super-frame. Although it aims to maintain fairness for all stations, the mobile stations are expected to experience long packet end-to-end delay if the number of stations is very large.

- (ii) The AP serves as a bridge between the mobile stations and the wired network (internet etc.). Extra buffering and processing delay are expected at the AP side for the mobile to mobile traffic which is routed through the AP.
- (iii) In an infrastructure BSS all the packets will go through the AP. This is not efficient for mobile to mobile communication.
 - Each data packet is required to be transmitted twice: mobile→AP then AP→mobile. This increases the collision probability and also increases channel utilization time.
 - As wireless transmission is subjected to higher BER, two-hop transmission will encounter a higher overall error rate than that for a single-hop transmission.
 - The AP will buffer packets from the source station until the time the destination station is polled. So data packets are expected to have longer end-to-end delay. This delay can be as long as the whole length of a super-frame if AP polls the destination station earlier than the source station.

Figure 5.1: Choose the transmission method based on position information

- The two-hop transmission may consume more energy than a direct single-hop transmission as illustrated in Figure 5.1. It is assumed that the receiver uses constant power for receiving a packet. A scheme that has been used in our proposed protocol to dynamically adjust transmission power of mobile stations is described in the later chapter, in which the overheard RSSI information [98, 99] of control frames is

used to estimate the minimal required power for packet transmission to other mobile stations. Furthermore, the AP is at a fixed known position and always transmits with fixed power, the transmission power required for mobile stations to maintain an acceptable SNR at AP can also be estimated based on the RSSI information of polling message from AP, which can be used by mobile stations to dynamically adjust their transmission power to AP. According to the basic theory of radio communication, the received signal strength is inversely proportional to some power of distance between the sender and receiver. To guarantee a fixed SNR at the receiver side, transmitted power should be adjusted proportional to D^λ ($2 \leq \lambda \leq 4$ for outdoor transmission), where D is the distance between sender and receiver.

It is assume the power required at mobile station 1 for direct transmission is $P_{1 \rightarrow 2}$ and for the transmission routed by AP is $P_{1 \rightarrow AP}$. So $P_{1 \rightarrow AP}$ is much larger than $P_{1 \rightarrow 2}$ as shown in Eq. 5.1, if $D_2 > D_1$ given that $2 \leq \lambda \leq 4$. As in this particular example, a direct transmission (MS1 $\rightarrow$ MS2) is more power efficient than the transmission routed by AP (MS1 $\rightarrow$ AP $\rightarrow$ MS2).

$$\frac{P_{1 \rightarrow AP}}{P_{1 \rightarrow 2}} = \left(\frac{D_2}{D_1}\right)^\lambda \quad (\text{Eq. 5.1})$$

- The transmission MS1 $\rightarrow$ AP $\rightarrow$ MS2 will occupy the shared wireless channel almost twice longer than a direct transmission MS1 $\rightarrow$ MS2. Both sender and receiver have to wait longer time in idle state, which is considered as a waste of energy.

(iv) Under PCF mode, there exists an option for mobile stations to reply the contention-free poll from AP by sending a frame to other mobile stations. However, due to the lack of the position information and operating state (in PS state) of destination, such transmission is not guaranteed and sometimes not even possible. So it is not actually implemented in most of the wireless LAN devices under an infrastructure BSS setup. As shown in figure 5.1, MS3 is either out of the transmission range of MS1, or requires much more energy than using AP as router to forward traffic.

5.3.2 Proposed Improved PCF Operation

Based on the above analysis, modifications to the PCF are necessary to achieve higher performance. In traditional PCF protocol of IEEE 802.11, right after the beacon transmission AP will poll the registered stations within the service set one by one in a round robin fashion. Upon reception of the polling message (without payload if there is no downlink data for the specific station), the station will return its uplink packets if there is any or return a packet without payload which indicates that it has no uplink packet. The modified version operates in two phases:

- (i) AP will poll all stations at least once. During the first polling phase, AP follows the traditional PCF operation, while stations will return the following information of their pending traffic instead of actual data packets.

- Number of pending packets for AP.
- Number of pending packets for other mobile stations.
- The destination address of mobile stations.
- The location information (calculated based on the RSSI information of the poll from AP).

So after this polling phase, all the downlink packets have been transmitted.

- (ii) AP will send a broadcast message to all mobile stations after the first polling, which enable those mobile stations with no pending packets to or from AP and other mobile stations to switch to the power saving state until next beacon period.

- (iii) Then AP will poll the stations that are still in the active state again.

- It will first poll the stations that only have pending packets for AP based on the traffic announcements received in last polling phase. The packet transmission procedure will be according to the original PCF mode. Upon reception of the polling

message, stations will acknowledge the polling by return their uplink packets. After the transmission, stations without any pending packets for other mobile stations can switch to the power saving state until next beacon period.

- If the location information of mobile stations can be obtained from a location service [100], mobile stations can utilize the distance information between each other to dynamically adjust their transmission power. In case such location service is not available, mobile stations can use RSSI measurements [1, 101, 102, 103] based on the overheard control frames to estimate the minimal necessary power for desired destination mobile stations. In our proposed protocol, as shown in Figure 5.1, MS1 has data packets for MS2. During the first polling phase, If MS1 is polled first, MS1 will announce its pending data packets as the reply to the poll. MS2 can then overhear the announcement which has MS2's AID as the destination address and calculate the RSSI from MS1. The RSSI value between MS1 and MS2 is transmitted to AP as piggyback information when MS2 is polled. If MS2 is polled first, MS2 will reply a frame without payload to AP since it does not have pending packets. MS1 can actively overhear the transmission and transmit the RSSI value between MS1 and MS2 to AP when it is polled.

The signal strengths between AP and mobile stations are monitor by AP constantly, while the signal strength information between different mobile stations is collected by mobile stations and reported to AP when polled. The mean of the most recent 20 signal strength values is then used in our proposed algorithm. Based on the RSSI information between different mobile stations and the traffic condition (mobile to mobile), AP will calculate the power required for routed transmission (mobile to AP to mobile) and direct transmission (mobile to mobile) as described previously. It will choose the transmission method based on the comparison. Stations that can only use AP to forward their mobile-to-mobile traffic (either because the source and

destination are out of transmission range, or the direct transmission is not power efficient, eg. MS1 to MS3) will be polled by AP for their pending packets subsequently. After the transmission, stations without any pending packets for mobile stations can switch to the power saving state until next beacon period.

- After all the stations that satisfy the above mentioned criteria have been polled, AP will signal the end of the contention free period by transmitting a control frame of subtype CF-End. If there is any mobile-to-mobile traffic pending, AP will piggyback the transmission order information [89] to schedule the AP assisted DCF transmission period to reduce any possible collision. The transmission order information as shown in table 3.1 includes the source and destination address of mobile stations, the number of pending packets and the scheduled transmission time. Stations operating in the contention period must follow the explicitly announced transmission order by AP, which can minimize the contention when multiple stations with pending packets try to access the channel simultaneously. The detailed procedure for AP and mobile station operation are illustrated in Figure 5.2 and Figure 5.3.

- (iv) During the direct transmission, if a specific packet has not been correctly acknowledged by the destination, the source mobile station will transmit the packet to AP during its next polling round as its uplink packets. AP will then retransmit the packets to the destination. It operates in the following procedure. Suppose A has a series of packets to be directly transmitted to B with sequence number 1, 2, 3, 4 and after the transmission of packet 2 to B, A has not received ACK from B within the ACK timeout. In this case, the transmission error is probably caused by random noise. In our proposal, A will try to retransmit packet 2 for only once. If the retransmission is successful, then remaining packets will be transmitted as usual. If the retransmission is not acknowledged either, A will stop the direct transmission and pass all the remaining packets to AP during the

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Figure 5.2: AP operation procedure of the enhanced PCF protocol

next polling. (In this case, the destination maybe in deep fading, out of range, or subject to interference). The detailed procedure for this mechanism is illustrated in Figure 5.4.

5.3.3 Signal Strength Measurement of Mobile Stations

In our proposed algorithm, the energy consumption of the routed transmission through AP and the direct transmission is compared based on the RSSI information between mobile stations and AP. Since we are not interested in the exact location of mobile stations, we do not have to use complex location system such as GPS [104, 105] or signal triangulation and probability based approaches [106, 107]. Mobile stations can actively measure the signal strength of other mobile stations (by overhearing their transmissions when they are polled by AP) or AP (by measuring the signal strength of AP when receiving polls from AP). In this section, experimental results of RSSI measurement are given to show that in practical scenarios the RSSI based method is able to provide sufficient and accurate information which can be used in our proposed algorithm

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Figure 5.3: Mobile station operation procedure of the enhanced PCF protocol

to determine the trade-off between direct transmission and routed transmission. Similar to other research context [98, 99], the accuracy of the RSSI measurement strictly depends on the propagation environment. In our discussion of chapter, a line-of-sight transmission environment is assumed. Recently, the Ultra Wide Band (UWB) radio is getting more and more popular for future communication and ranging applications. There are two time-based positioning techniques in UWB based wireless system: Time of Arrival (TOA) and Time Difference of Arrival (TDOA), which rely on measurements of travel times of signals between nodes. For non-line of sight transmission, the UWB based estimation approach can be used [108]. However, it

Figure 5.4: The AP-assisted retransmission mechanism

is out of the scope of our thesis. Furthermore, the well-known hidden/expose node problem [48] can also introduce error to the RSSI measurement based location determination. However, our proposed protocol is based on infrastructure network, which does not fully rely on CSMA/CA based mechanism. By using centralized polling and scheduling and assuming all participating mobile stations following the schedule, our proposed protocol is affected by the hidden/expose node problem.

Figure 5.5: CeMNet floor plan with illustration of the experiment setup

In the experiment, we try to get the signal strength values of wireless connection from a single

AP which is located approximately in the center of our CeMNet research laboratory. The signal strength values have been obtained at 15 locations within CeMNet, and they are illustrated as a dotted line in figure 5.5. The distance between consecutive locations is approximately 3 meters. The laptop computer which is equipped with a wireless LAN card is placed at a higher position, so there is no significant obstacle in the line-of-sight between each testing point and the antenna of the AP. At each testing point, 100 signal strength values are collected at the intervals of 0.5 second. During the post data processing, we notice that there are significant data variations at the beginning of each test. The reason for this behavior is probably that the wireless card is not in the fully working condition during the switching between idle state and passive reception state. So the later 80 values are used in our analysis.

Figure 5.6: Signal Strength Variation at Different Location

The signal strength values (db) at different locations are illustrated using different symbols in Figure 5.6. A non-linear curve-fitting algorithm is also used to show that the received signal strength values at each fixed location have a strong tendency to be a constant value if the outside condition does not change. The only factor that significantly affects the received signal strength is the distance between sender and receiver.

Figure 5.7: Mean of Received Signal Strength Value at Different Locations

Figure 5.7 shows the mean of received signal strength at different locations. Location 1 is at one end of CeMNet lab and against wall. The signal is likely to be affected due to multi-path effect. Location 7 and 8 are the nearest points to the antenna of AP. In our proposed algorithm, the mean of the RSSI is also used as the metric as described in previous section. The change in distance between mobile stations and AP is reflected by the signal strength variation significantly.

Figure 5.8 shows the signal strength variation at different locations. In this figure, the relationship between the location and the received signal strength values is illustrated clearly. Even in the indoor environment, the received signal strength changes significantly when distance between sender and receiver changes, but at a fixed location the signal strength tends to remain at a rather constant level. So the source mobile station can dynamically adjust its transmission power based on the RSSI information to guaranty a constant and acceptable SNR at the destination.

5.3.4 Proposed Smart AP Protocol

In this section, a smart AP protocol is introduced by utilizing the results from our analysis of the expected reply delivery time of traffic between mobile stations and a remote sever attached

Figure 5.8: 3D Map of Received Signal Strength Variation at Different Locations

to AP through wired line. The smart AP protocol aims at reducing the end-to-end delay of traffic between AP and mobile stations through a waking up time estimation using historical delay information. Furthermore, smart AP protocol also reduce energy consumption of mobile stations, since mobile stations stay in active state in specific beacon interval only if they have packets for AP or the replies from remote server are already buffered at AP and ready to be transmitted to mobile stations. Using the proposed protocol, mobile stations stay in power saving state for longer period of time and not all mobile stations are required to stay in active state in every beacon interval. The number of mobile stations that have to be polled by AP in every beacon interval is reduced which reduce the end-to-end delay and increase the throughput of the traffic between AP and mobile stations.

5.3.4.1 Analysis of the Expected Reply Delivery Delay for Waking Up Time Determination of Mobile Stations

In order to further extend the improved PCF operation, analysis and experimental results of end-to-end delay in a client-server communication scenario is presented. A smart AP protocol is proposed on top of the improved PCF operation as an extension, which determines the waking up time of mobile stations in the power saving mode using models derived from the expected

reply delivery time analysis. In our analysis and simulations, we assume an infrastructure based wireless LAN environment with a single AP and mobile stations within its coverage area. The AP is connected to a remote server with wired link. Mobile stations send request to the remote server and wait for the reply message. In this scenario, the request has to be transmitted to AP first, which acts as a common gateway between mobile stations and external network. The AP forwards the request to the remote server and buffers the reply from it. The buffered information will be transmitted to the desired mobile station when it is in active state and polled by AP.

The major difference between improved PCF operation and smart AP protocol is the beacon transmission procedure. In our proposed smart AP protocol, when AP transmits the beacon at the beginning of each beacon interval, it also piggybacks the Traffic Indication Message (TIM) [1] to the original beacon. The TIM is generated based on all the reply packets that have been received from the remote server by AP and have not been transmitted to mobile stations. The stations with their addresses listed in the TIM will stay active to receive the pending reply packets forwarded by AP in the first polling phase after the beacon transmission. Other stations with their addresses not listed in the TIM can switch to power saving state if they do not have data packets to send. Based on our improved PCF operation, two-phase polling mechanism is used and the first polling phase is utilized for downlink traffic and collection of traffic information. So stations with pending mobile-to-mobile or mobile-to-AP traffic are still required to stay in active state and report information of their pending traffic as the reply to AP's poll using the procedure described in previous sections. Using the TIM, the stations that have transmitted requests in previous beacon intervals and still wait for their replies from the remote server to be received by AP have a chance of switching to PS state after reception of the beacon. Hence, these stations will not be polled by AP in current beacon interval if they do not have packets pending to send. If other stations still have pending packets for these stations, the packets are transmitted to AP and buffered, which can be delivered to the destination mobile stations in the following beacon intervals by notifying them using TIM.

Based on the above description, the following analysis of the expected reply delivery delay of the traffic between mobile stations and the remote sever is derived.

(i) Fixed wired line delay

The Round Trip Time (RTT) between the AP and remote server is a fixed value (an approximated value) D . This represents the scenario where the remote server is connected with AP through reliable connections such as LAN. It is assumed that the processing time of the request at remote server is negligible compared with the transmission delay. So the expected end to end (mobile to remote server) reply delivery delay is also D , if the propagation delay between mobile stations and AP is also neglected. However, transmission time is divided into a series of beacon intervals and in our proposed smart AP protocol the downlink packets are delivered during the first polling phase at the beginning of each beacon interval. To consider the lower bound of the reply delivery delay, it is assumed that AP will transmit the buffered reply to the destination immediately at the beginning of a beacon interval if it has received the reply for designate destination in previous beacon interval. So the reply packets can be delivered to mobile stations in a specific beacon interval only if they have already been received by AP during previous beacon interval. Furthermore, if a request packet is generated at a specific mobile station before the station is polled, the packet may be transmitted to AP in current beacon interval when the station is polled. On the other hand, if the request packet is generated after the station is polled, it has to wait until the station is polled by AP in the next beacon interval.

We can see that the length of the beacon interval (B) and the time the request is sent (T) within current beacon interval are two major factors that affect the expected reply delivery time significantly. Figure 5.9 to 5.11 are used to describe the expected reply delivery delay for the fixed wired line delay scenario. The X-axis is the request sending time within current beacon interval and Y-axis is the expected reply delivery delay.

- $0 < D < B$, Figure 5.9 can be used to describe the expected reply delivery delay at destination mobile station. Therefore, if a request is transmitted to AP (as a

Figure 5.9: Lower bound of the Expected Reply Delivery Delay Time with $0 < D < B$

reply to AP's poll) at time $B_i + T$ in current beacon interval B_i with the length of the beacon interval equaling to B , the mobile station is expected to receive the reply from the remote server in the beginning of next beacon interval B_{i+1} at time B_{i+1} , if $T + D < B$ (which means AP receives the reply from remote server within beacon interval B_i). If $T + D > B$ (which means AP receives the reply from remote server within beacon interval B_{i+1}), the mobile station is expected to receive the reply in the beginning of next beacon interval B_{i+2} at time B_{i+2} . The lower bound of expected reply delivery time to destination mobile stations is described using the following equations:

$$Delay = \begin{cases} B_i + B, & \text{if } T + D < B; \\ B_i + 2B, & \text{if } T + D > B. \end{cases} \quad (\text{Eq. 5.2})$$

- $B < D < 2B$, Figure 5.10 can be used to describe the expected reply delivery delay at destination mobile station. The lower bound of expected reply delivery time to destination mobile stations is described using the following equations:

$$Delay = \begin{cases} B_i + 2B, & \text{if } T + D < 2B; \\ B_i + 3B, & \text{if } T + D > 2B. \end{cases} \quad (\text{Eq. 5.3})$$

Figure 5.10: Lower bound of the Expected Reply Delivery Delay with $B < D < 2B$

- In general cases $kB < D < (k+1)B$, Figure 5.11 can be used to describe the expected reply delivery delay at destination mobile station. The lower bound of

Figure 5.11: Lower bound of the Expected Reply Delivery Delay with $kB < D < (k+1)B$

expected reply delivery time to destination mobile stations is described using the following equations:

$$Delay = \begin{cases} B_i + kB, & \text{if } T + D < (k+1)B; \\ B_i + (k+1)B, & \text{if } T + D > (k+1)B. \end{cases} \quad (\text{Eq. 5.4})$$

Using the expected reply delivery time, the power state transition pattern of mobile stations that have transmitted the request can be easily determined. Therefore, mobile stations can decide when to switch to power saving state and when to stay in active state

to receive the buffered data from the AP based on the time they have transmitted the request.

(ii) Variable wired line delay

The RTT between the AP and remote server is not a fixed value but a random value P_{rtt} uniformly distributed within the range of $[Delay_{lowbound}, Delay_{highbound}]$. This represents the scenario where the remote server is connected with AP through unreliable connection such as Internet. We provide the simulation results of the expected reply delivery delay with a simulation program. The simulation program uses the similar assumption that we have described previously.

The following figures show the relationship between expected reply delivery delay and request sending time. The beacon interval is 100ms in the simulation, and a scenario that there is a request every 1ms is simulated. The queuing time and contention within the service area are currently ignored and the transmission time between mobile stations and AP is also neglected.

Figure 5.12: Expected Reply Delivery Delay with delay range $[0, 20]$

Based on the above analysis and simulations, the actual request sending time and the length of the beacon interval decide the time that mobile stations are expected to receive their replies. If mobile stations do not have any uplink packets to AP, they should not stay in active state earlier than the time the replies are expected to be ready at the AP side, otherwise mobile

Figure 5.13: Expected Reply Delivery Delay with delay range $[20, 40]$ Figure 5.14: Expected Reply Delivery Delay with delay range $[20, 50]$

stations wait in idle state and waste their energy. Furthermore, AP has to poll the active mobile stations even they do not have any uplink and downlink packets, which also reduces the available bandwidth. In our proposed smart AP protocol, mobile stations use the average of the last five observed reply delivery delay to estimate the actual end-to-end delay and use the models described above to determine the actual time they have to stay in active state instead of staying active for every beacon interval. If mobile stations wake up and the replies have not been received by AP yet, they are instructed to switch to power saving state using TIM by AP unless they have other mobile-to-mobile or mobile-to-AP packets waiting.

5.4 Simulation and Analysis

In order to verify our proposed algorithm as it is incorporated into existing IEEE 802.11 protocol and provide comparison results, the well-known network simulator NS-2 version 2.1b8 [109] with contributed PCF model provided by Anders Lindgren [110] is used, which has a detailed

Figure 5.15: Expected Reply Delivery Delay with delay range [50, 100]

Figure 5.16: Expected Reply Delivery Delay with delay range [100, 150]

simulation of the MAC/PHY layer characteristics and infrastructure based operation of IEEE 802.11. Our proposed modifications is implemented on-top of the existing model. In the simulation, a wireless LAN environment is setup with AP and mobile stations. The physical layer is modeled as the 2Mbps wireless medium as widely used in most of the IEEE 802.11 compatible devices. The physical data rate dose not significantly affect the results, since the MAC level protocol operate basically in the same way for different data rates and modifications are only made on MAC level. The simulation area is a flat square ($500 \times 500 m^2$), and the AP is a special node with infinite energy and fixed position which is located in the center (250,250) of the simulation area. The total number of mobile stations in the simulation area is 20 and they are randomly deployed within the area. The constant bit rate traffic is used with fixed length packet size of 1024 bytes. The beacon interval is set to be 1 second and the max duration of the CFP is 0.8 second for PCF mode. The default energy consumption model is described in table 5.1. It is assumed that mobile stations use fixed energy level for receiving, idle and power-saving

state. The transmission power is adjustable and only applicable for data packets. As a result, mobile stations use maximum transmission power ($P_{transmitting}$) for communication during the first polling phase and control packets. Based on the estimated distance (D_{est}) between sender and receiver, equation Eq. 5.5 can be used to obtain the minimal required energy (P) for the transmission.

$$P = P_{transmitting} \times \left(\frac{D_{est}}{D_{range}}\right)^\lambda \quad (\text{Eq. 5.5})$$

Table 5.1: Energy Consumption Model

Operation mode	Energy
Idle	1.15 W
Power saving mode	0.045 W
Receiving	1.4 W
Transmitting ($P_{transmitting}$)	1.65 W
Transmission range (D_{range})	250 m

UDP traffic is used at each source with constant packet generation rate at 4 packets per second. The connection patterns are randomly generated. In Figure 5.17 to 5.19, the X-axis "number of stations polled by AP" means the number of stations that are communicating with each other using the AP as the router, in which the traffic sinks are at the destination stations (mobile stations). It should be noted that all other stations communicating with AP have their destination addresses of UDP traffic set at a remote server attached to AP. The simulation time is 200s and all the UDP traffics start at 7s together. In the simulation, the traditional IEEE 802.11 protocol is compared with our proposed modifications: the improved PCF operation and smart AP protocol. In our protocols, the mobile stations take advantage of the AP assisted DCF transmission mechanism for direct transmission between each other without routing through AP if certain criteria are met. Mobile stations do not have to stay active in every beacon interval owing to the waking up time estimation and announcement

Figure 5.17: Average packet end-to-end delay.

of TIM through beacon transmission. In the simulation, IEEE 802.11 PCF protocol has the minimum end-to-end delay as shown in Figure 5.17. The average delay calculation includes stations with packets destined for remote server and mobile stations. Suppose that a total of N packets have been received successfully, then the average delay can be calculated as described in equation Eq. 5.6,

$$average_delay = \frac{\sum_{i=1}^N (rcv_time_i - gen_time_i)}{N} \quad (\text{Eq. 5.6})$$

where rcv_time_i represents the time i_{th} packet is successfully received, and gen_time_i is the generation time of i_{th} packet.

There are several reasons that affect the results. In IEEE 802.11 PCF, stations will stay active for the entire beacon period. After all the stations in the polling list have been polled, AP can poll any station that has down-link data packets pending. Packets that are generated or received during the polling period can still be transmitted to mobile stations if the contention free period is not over. Furthermore, in our proposed algorithm, a two-phase polling mechanism is used during which the first polling period is utilized for traffic information collection. So the average time that a station with pending data is polled is larger than that in the traditional IEEE 802.11 PCF protocol, especially when the number of stations in the polling list of AP is

very large. Our smart AP operation has a performance gain over the optimized PCF, since an estimation of the wake up time is used to decide the stations' power state transition. Stations only stay in active state at specific polling period during which the reply from the remote server is expected to be received. So the number of stations that wake up during each contention free period is reduced, which reduces the length of polling list. So the average time that a station with pending data is polled is less than that in the improved PCF protocol.

Figure 5.18: Energy consumption per packet.

Energy consumed per packet is computed for each packet received at the destination, which accounts for the average energy consumed by each successfully received packet. It can be described as equation Eq. 5.7,

$$energy_per_packet = \frac{total_energy_consumed}{total_packet_received} \quad (Eq. 5.7)$$

The proposed protocols lead to less energy consumption per packet than IEEE 802.11 PCF, which may prolong the battery lifetime up to 35% in the best scenario as shown in Figure 5.18. Stations do not have to stay active for the entire contention free period unless it has setup schedule with AP during the first polling period, otherwise energy is wasted since stations wait in an idle state without receiving or sending any data packets. The two-hop transmission is also reduced to a single hop direct transmission if necessary for power efficiency. Stations can

switch to power saving mode after receiving the first poll, if they do not have packets to transmit or receive. Stations can also switch to power saving mode after the second poll, if they have finished the packets transmission and no direct transmission (AP assisted DCF) is scheduled by AP. If there is only traffic between the mobile stations and remote server (number of nodes polled equals 0), the energy saving can be maximized using smart AP operation. Stations don't have to wake up earlier than the time that the expected reply reaches the access point, which shorten the time that stations wait in idle state without receiving or sending any data packets.

Figure 5.19: Total packets transmitted during the simulation time

Figure 5.19 shows the number of data packets that have been transmitted and successfully received by the destinations. Since all the simulations run for the same amount of time and the traffic arrival rate, more packets transmitted suggests higher bandwidth utilization. Our proposed protocol utilizes the beacon interval as long as possible for the two-phase polling if most traffic is between AP and mobile stations. When most traffic is between different mobile stations, our scheme enable them to be directly transmitted during contention period. Furthermore, the two-hop transmission is reduced to a single hop direct transmission without contention, which reduces the channel utilization and possibility of collision. Hence there will be more time in each contention free period for stations that actually have pending data packets, which increases the throughput significantly. The smart AP operation has a noticeable

performance gain over the improved PCF operation mainly due to the estimation of the waking up time through the implementation of the TIM. Mobile stations use the historical traffic information and the delay model to estimate the expected reply delivery delay. Based on the estimation and the time that a request is sent, mobile stations are able to get approximate time that the replies are expected to be received. Using this information, stations can be instructed efficiently to stay in active state at specific contention free period which reduce the energy consumption. Since stations do not have to stay in active state during every contention free period, the length of the polling list of AP is also reduced. So there will be more time in each contention free period for stations that actually have pending data packets, which increase the throughput significantly.

5.5 Conclusion

In this chapter, a smart AP operation as enhancement to the traditional IEEE 802.11 PCF protocol is proposed. Simulation results show that using the proposed protocols energy consumption of mobile devices can be reduced while the end-to-end packet delay is slightly longer than traditional IEEE 802.11 PCF protocol. The throughput is increased significantly due to the reduction of channel utilization through the direct transmission and waking up time estimation. The proposed protocol is a hybrid of AP assisted DCF and PCF operation, which is more flexible and fault-tolerant, and can be readily reverted to the traditional IEEE 802.11 protocol for compatible reason when required.

Chapter 6

A Modified Time Synchronization Function in IEEE 802.11 protocol Using Differentiated Contention Window

Time synchronization is a very important design issue of MANET, especially when synchronous protocol is used, in which simultaneously launching of an event is required, or in some applications where the order of events is of great interest. The IEEE 802.11 standard for wireless LAN specified a DCF mode, which is designed for the ad-hoc communication. TSF has been defined as an essence component to the Frequency Hopping Spread Spectrum (FHSS) physical layer and the PSM. In the PS mode specified for DCF, TSF require that all nodes switch to active state and use contention based backoff mechanism to transmit the time synchronization beacon during each Target Beacon Transmission Time (TBTT). This chapter presents a modification to the existing TSF for DCF by using different backoff counter range according to the clock accuracy of the nodes. Using the proposed method, the probability of collision among beacons can be significantly reduced. So less time is required for the successful transmission of beacon frames, which, in terms of energy efficiency, is equivalent to less energy. Furthermore, the clocks can be converged quickly and a smaller clock deviation can be achieved compared with previous approach.

This chapter is based on the following paper:

M. H. Ye, C. T. Lau and A. B. Premkumar, "Modified Time Synchronization Function in IEEE 802.11 Using Differentiated Contention Window", in *the Fourth IEEE International Conference on Information, Communications & Signal Processing and Fourth Pacific-Rim Conference on Multimedia (ICICS-PCM 2003)*, December 2003, Singapore.

6.1 Introduction

Recent years, the concept of ad-hoc mobile network has attracted a lot of research interests, which is characterized by its flexibility and mobility. In such network scenario, all the autonomous mobile hosts are operating in a homogenous and distributed manner. Communication is peer-to-peer based and no existing network infrastructure is required. Time synchronization is a very important issue in the distributed computing environment for the communication protocol requirements and many application purposes [111, 112, 113].

In the IEEE 802.11 standard, the radio implementations of the physical layer specify either a FHSS or a Direct Sequence Spread Spectrum (DSSS). In the FHSS system, each mobile station determines the time by its local clock when to hop to the next frequency channel. When using the PS mode in both the FHSS and DSSS system, transmission time is divided into so-called beacon interval and at the beginning of each beacon interval there is a common awake period denoted as the ATIM window, which require that all the stations wake up and stay in the active state to announce their pending data packets. Time synchronization is required for each station to decide the exact beginning and end time of each ATIM window. Since time and order of events is only relevant within the IBSS [114, 115], the TSF specified in 802.11 standard only serves the purpose of synchronizing the peering nodes' local clock to a common value regardless the difference from the real world clock. It is a different concept from some well-known Internet timing synchronization protocols, such as Network Time Protocol (NTP) [116], in which external connections to the GPS system [117] or the atom clocks are available through reliable links that can provide a reference to the real world clock.

6.1.1 TSF Specified for IEEE 802.11 DCF Mode

Figure 6.1: Time Synchronization Function Specified for IEEE 802.11 DCF

Since the accuracy of the Quartz-Crystal Oscillator based clock is significantly affected by many factors, such as temperature, change of current or voltage [118, 119], even synchronized clocks will have intolerable difference after certain time. The TSF of IEEE 802.11 [1] is implemented through the distributed beacon frame transmitted by contention at nominal rate denoted as *BeaconInterval*. The TSF require that each mobile station shall maintain a TSF timer with modulus 2^{64} counting in increment of microseconds [1]. In each TBTT, which is exactly *BeaconInterval* time units apart, each mobile station within the IBSS contends to transmit the beacon frame. Each mobile station calculates a random delay uniformly distributed in the range between 0 and $2 \times CW_{min}$ (CW_{min} is the minimum contention windows used in the backoff mechanism), and wait for the period of the delay time using the backoff mechanism. If the delay counter expired, beacon will be transmitted bearing a timestamp which is a copy of the sender's local TSF timer with some adjustment. Mobile nodes will cancel the beacon transmission if a beacon arrives before its random delay counter expired. When a beacon is successfully received, a station sets its TSF timer to the timestamp of the beacon if the value of the timestamp is later than the station's TSF timer. As a result, TSF timer can only move forward.

6.1.2 Related Works

In IEEE 802.11 TSF, although stations will have equal priority in the beacon transmission if they follow the above-mentioned procedure with the same contention window size, the influence of the beacon depends in the beacon sender's clock accuracy. Typically a beacon transmitted by a station with faster clock tends to synchronize a larger portion of the mobile stations. To some extent, this leads to another kind of unfair problem, since the stations with fastest clock cannot be synchronized by the stations with slower clock. Consequently the TSF timer of the stations with fastest clock will drift away from all other stations if they are not able to win the beacon contention for several consecutive beacon intervals.

This problem has been investigated in [120], they have also presented a protocol, named ATSP, with slightly modification to the TSF of 802.11. In ATSP, initially each node is assigned an integer value I randomly chosen within the range of $[1,10]$, which is adjusted every time a beacon is successfully received. Value I represents how frequent a station will participate the beacon contention (every I beacon intervals). Stations will slowly increase I when receive a timestamp larger than its local TSF timer, which means they increase the interval that they join the beacon contention, and vice versa. Network is stabilized when value I of the fastest stations reaches 1, and all the other station have I equal to a predefined value, which is 10 in their simulations. When a station joins the service set with a faster clock than all the existing stations, network re-establishment is required. Similarly, this also applies to the scenario when the fastest station leaves the IBSS. Furthermore, when the number of nodes within the IBSS is very large, then because every beacon interval averagely 10% (in [120], they chose I equal to 10) of the nodes will join the beacon contention with the fastest stations, a higher collision probability among beacons is expected. The fastest stations cannot be guaranteed to transmit the beacon. So it will not be the optimize method to achieve a smaller clock deviation when the network size is very large.

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In [121], they proposed a modification to the time synchronization procedure of IEEE 802.11 PCF. The time synchronization function for PCF is relatively easy to implement, since there exists a single Access Point which controls the channel access and acts as the timing master. In such a Master-slave operation mode, precision of synchronization can be enhanced by reducing the time-critical path of the protocol from the master to slaves. The synchronization protocol of IEEE 802.11 works as follows as illustrated in Figure 6.2: the master takes its local time-stamp (t_1) and broadcasts it at t_2 . All slaves physically receive this message at their network interface cards at t_3 and adjust their local clocks at t_4 . The precision that can be achieved is bounded by the variance of the time-critical path. In this approach the time-critical path is the time between the master takes its time-stamp and the slaves adjust their local clocks (t_1 to t_4). The modified version operates as illustrated in Figure 6.3: Each slave (and the master) receives the indication message (t_3) and takes a local time-stamp (t_5). Calculating and adjusting new slave clock values (t_4) is not needed at this time. Then the master sends its own time-stamp for the last indication message (t_5) and each slave compares the master's time-stamp with its own time-stamp for the reception of the last indication message, computes the difference and adjust its local clock (t_6).

Figure 6.2: Time Synchronization Function of IEEE 802.11 protocol

Figure 6.3: Modification of Time Synchronization Function of IEEE 802.11 protocol

6.2 Proposed Modification to the Time Synchronization Function

This section presents a more scalable method by using differentiated backoff counter range for stations with different clock accuracy. Our approach is based on modifying the backoff mechanism for beacon transmission. It can be easily incorporated with the existing TSF and is very useful to solve the asynchronism problem and to achieve a smaller clock deviation. It has three phase denoted as the Initialization phase, Stabilized phase, and Repairing phase.

6.2.1 Initialization Phase

On reception of a beacon, there are two possible out comings. Denote T_{cur} as nodes' clock when the beacon is received and T_{recv} as the received timestamp within the beacon:

- $T_{cur} > T_{recv}$, the station probably has a fastest clock.
- $T_{cur} \leq T_{recv}$, the station probably has a relatively slower clock.

So the backoff mechanism for beacon transmission of next beacon interval can be modified as following. On reception of the beacon, each node will decide whether or not it will join the beacon contention in the next beacon interval based on the following algorithm:

Wherein $\text{RNG}(0,1)$ is a function that returns a uniformly distributed random float number within the range of $[0,1]$, and $\text{probability}(T_{cur} - T_{recv})$ is the function that returns a probability

Algorithm 6.1: Algorithm for calculating the backoff counter for next beacon contention

```

1: if  $T_{cur} > T_{recv}$  then
2:    $backoff\_counter = RNG(0, 1) \times CW_{min} \times 2$ ;
3: else
4:    $backoff\_counter = RNG(0, 1) \times CW_{min} + CW_{min}$ ;
5: end if
6:  $probability(T_{cur} - T_{recv})$ ;

```

for the P-persist method, which is used for a node to decide whether or not it will join the next beacon interval. The P-persist method is used to reduce the number of stations that join the beacon contention. So the stations with its local TSF timer faster than the received timestamp will adapt the backoff counter range of $[0, 2 \times CW_{min}]$. All other stations with their local TSF timer slower than the received timestamp will use the backoff counter range of $[CW_{min}, 2 \times CW_{min}]$, which will decrease their probability of winning the beacon transmission. The operation diagram is illustrated in Figure 6.4.

Figure 6.4: Initialization Phase of the Proposed Modification to the Time Synchronization Function

If a specific node has successfully transmitted beacons for consecutive 3 beacon interval, the backoff counter range will be changed to the next stage, which is the stabilized state. The specific station will calculate its backoff counter which is randomly distributed within the range

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of $[0, \frac{CW_{min}}{2}]$, while all other stations that have listened and adapted the beacons will calculate their backoff counter ranging between $[\frac{CW_{min}}{2}, 2 \times CW_{min}]$ for the future beacon transmission.

A smaller backoff counter range $[0, \frac{CW_{min}}{2}]$ is adapted as the contention window size for the fastest stations. The fastest stations that already reside in the IBSS can use this contention window to reduce the beacon collision probability among them, while any station that joins the IBSS can also use this contention window to compete with the existing fastest stations to quickly re-establish the network if necessary. Both the simulation and analysis show that this range is capable of reducing the collision and achieve a smaller beacon transmission time.

6.2.2 Stabilized Phase

In the stabilized phase, the fastest stations will generate their backoff counter for the beacon within the range of $[0, \frac{CW_{min}}{2}]$, and it is independent of all the other stations because the backoff counter range is separated. The slower stations will not interfere with the beacon transmission of the fastest stations. As a result, the beacon transmitted by the fastest station is guaranteed to have less collision probability comparing with the previous approach, and is able to synchronize almost all other stations' clock. Furthermore, the proposed mechanism is fault tolerable, since P-persist method will guarantee that sufficient station will join the beacon contention in each TBTT. The operation diagram is illustrated in Figure 6.5.

Figure 6.5: Stabilization Phase of the Proposed Modification to the Time Synchronization Function

6.2.3 Repairing phase

When a station joins the service set with a faster clock than all the existing stations or the fastest station leaves the IBSS, re-establishment is needed.

- When fastest station leave the IBSS:

After the stabilization, nodes are expected to receive beacon before the expiration of $\frac{CW_{min}}{2}$ slots time of the backoff counter. If a node dose not receives a beacon within that range, it will assume that the fastest station has left the IBSS, and will fall back to the initialization phase.

- When a new station join the IBSS:

When a new node joins the IBSS, it will follow the procedure to scan and adapt the parameter of the IBSS. Upon receipt of the first beacon frame, it can decide the contention window range that it should use. If a timestamp received from the beacon is smaller than its own, it will use the backoff counter range of $[0, \frac{CW_{min}}{2}]$ to compete with the existing fastest stations using the mechanism defined in the initializing phase. If not, it will directly adopt the range of $[\frac{CW_{min}}{2}, 2 \times CW_{min}]$ to avoid collision with existing fastest stations.

Following the above-mentioned procedure, the proposed algorithm, which has a small re-establishment time, is very suitable for the scenario where rapid network topology change is unavoidable.

6.2.4 Scalability of Beacon Contention in IEEE 802.11

Given an fixed backoff window (CW_{min}) in beacon transmission, it is relatively easy to analyze the probability of a beacon collision. The probability that a station attempts to transmit in an arbitrary time slot is given by $\frac{1}{CW_{min}}$. The probability that during the beacon transmission of an arbitrary station there is no other active station is $(1 - \frac{1}{CW_{min}})^{n-1}$. The beacon collision probability p is described in the following equation Eq. 6.1:

$$p = 1 - \left(1 - \frac{1}{CW_{min}}\right)^{n-1} \quad (\text{Eq. 6.1})$$

The equation is plotted in the following figure 6.6 using number of mobile stations as variable to show the collision probability of beacon transmission.

Figure 6.6: Collision Probability of Beacon Transmission

As shown in the above figure, in IEEE 802.11 the probability of a beacon collision is very high when the number of mobile stations in the IBSS is increased. By using a separated contention window to avoid beacon collision, our proposed protocol can tolerate more mobile station in an IBSS.

6.2.5 Results of Modified Approach

The proposed algorithm not only solves the asynchronism problem, but also improves the network performance. In proposed algorithm, the contention window is partitioned into windows of smaller range, and each station adaptively select the prioritized range. The high priority part of the contention window (the frontal slots) can only be used by stations that have a faster timer than the last beacon sender. Hence the prioritized contention window range guarantees

that stations with faster clock will have higher probability of winning the beacon contention. Owing to the disjoint contention window and the P-persist mechanism, the collision probability of beacon transmission can be significantly reduced which makes the proposed algorithm more scalable. As a result, less time is needed for sending each beacon (from the beginning of the TBTT to the time when a beacon is successfully transmitted), which is equivalent to less energy consumption. A smaller clock deviation can also be achieved by having the fastest station transmitting the beacon with high probability. Network can be stabilized quickly which means that the proposed algorithm is more suitable for the scenario where network topology changes from time to time. Simulation results show that there are significant improvement over IEEE 802.11 and previous approach in [120]. Figure 6.2.5 shows the standard deviation of all the stations clock after the beacon transmission. The proposed algorithm has a smaller clock deviation, which means it is better than 802.11 and that proposed in [120] as far as the convergence of the clocks to a common value is concerned. In Figure 6.7.b, the average beacon transmission time of the three protocols is compared. Since in the proposed algorithm, the faster stations are granted high priority in beacon transmission by the assigned contention window that inhabits the the frontal part of the original beacon contention window, beacon transmission time is significantly less than the other two protocols which is more efficient in energy consumption and bandwidth utilization. Table 6.1 compares the network stabilization time of the proposed algorithm and [120]. In [120], network is stabilized when the parameter I of the fastest station is equal to 1 and all other stations have their I equal to 10 [120]. In proposed algorithm, it is the time when a specific station have successfully transmitted beacon for consecutive 3 beacon intervals. The shorter stabilization time of the proposed algorithm implies that it is adaptive to the scenario when stations join or leave the service set frequently.

6.3 Conclusion

This chapter presents a modified TSF for IEEE 802.11 DCF mode. A new backoff mechanism is introduced by prioritizing the beacon transmission by the clock accuracy of mobile stations.

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6.7.a: Standard Deviation of Stations' TSF Timer

6.7.b: Average Beacon Transmission Time

Figure 6.7: Comparison of Clock Deviation and Average Beacon Transmission Time

Table 6.1: Average time to stabilize the network (number of beacon intervals)

Number of stations	50	100	150	200	250	300
ATSP	55.55	54.05	44.1	43.05	42.65	51.55
Proposed	11.3	15.85	14.5	17.9	13.25	18.2

The disjoint backoff counter range will give the fastest stations higher priority in the beacon transmission. As a result, the collision probability of beacon transmission can be significant reduced. So less time is needed for each beacon transmission, which is equivalent to less energy consumption. A smaller clock deviation can also be achieved by having the fastest station transmitting the beacon with high probability. Owing to the fast convergence ability, network can be stabilized quickly which is more suitable for the scenario where network changes rapidly from time to time. Simulation results show that there are significant improvement over IEEE 802.11 and ATSP.

Chapter 7

Enhanced IEEE 802.11 Power Saving Mode Using Battery Recovery Effect

7.1 Introduction

This chapter presents an enhancement to the existing power saving mode as stipulated in IEEE 802.11 protocol by taking advantage of the battery recovery effect. Based on the low level battery discharging model, an enhancement to IEEE 802.11 is proposed to efficiently exploit the battery capacity that improves the battery lifetime of portable devices significantly. The basic idea is to enable the battery to recover its charge by actively deferring the transmission attempts, which may incur some additional packet delay. However, in most of the services and applications that are not strictly time-critical, such as web browsing and sensor network, longer operation time is often preferred. Our proposed power efficient protocol, which can be easily incorporated to the existing power saving mode of IEEE 802.11, is ideally suitable for such applications.

This chapter is based on the following paper:

M. H. Ye, C. T. Lau and A. B. Premkumar, "Enhanced IEEE 802.11 Power Saving mode using Battery Recovery Effect", in *the 7th IEEE International Symposium on Consumer Electronics 2003*, December 2003, Sydney, Australia.

The remaining of the chapter is organized as follows. Section 2 gives a background introduction of the battery technology, especially the battery recovery effect. Section 3 briefly

reviews the power saving mechanism specified in IEEE 802.11 standard and related works that take advantage of the battery recovery effect. Section 4 presents our proposed enhancement to power saving mode of IEEE 802.11 protocol to achieve energy efficiency. Section 5 describes the simulation model and results which shows the advantage of our proposed algorithm. Section 6 concludes the chapter.

7.2 The Battery Recovery Effect

Battery technology has been given a lot of research interests, which is stimulated by the power demand of more and more mobile electronic devices.

A battery is made up of one or more electrochemical cells. Each cell consists of an anode, a cathode and the electrolyte that separates the two electrodes. As the result of electrochemical reactions occurring at the electrode-electrolyte interface, electrical current can be generated. With a non-zero discharge current, the active elements are consumed at the electrode-electrolyte interface. However, the active elements can also be compensated by new active material that moves from the electrolyte solution to the electrode through the diffusion mechanism. The cell voltage will decrease when the intensity of the current is increased. This phenomenon is known as the rate capacity effect in battery technology as described in [122, 123, 124, 125]. If the discharge current is above a threshold value, the diffusion phenomenon can not be able to balance the depletion of active elements. The cell voltage will very quickly drop below the cut-off value, and the battery cell is considered discharged. However, in this case the theoretical capacity of the cell has not been exhausted. So it is not the efficient way to use battery power. The high specific energy can be obtained if a low specific power is drawn. As shown in Figure 7.1, for the lithium-ion battery the delivered capacity increases by more than 50% when the specific drawn power is reduced from 4W to 1W [126, 127].

Based on the above mentioned diffusion process, it shows that the lifetime of a battery also depends much on the discharge demand profile. If a battery is discharged for short time intervals

Figure 7.1: Continuous discharge behavior of a lithium-ion cell [127]

follows by idle periods that are sufficient long, significant improvement in delivered energy can be achieved. This is because that during the idle periods the battery can partially recover the capacity lost while delivering current impulses [128]. This mechanism is called recovery effect. Under a non-continuous discharge profile, the recovery effect can lead to a significant improvement in battery performance.

7.3 Related Works

7.3.1 Power Saving Mode of IEEE 802.11 Protocol

The power saving mode of IEEE 802.11 is an optional enhancement to the basic access procedure that aims to reduce the power consumption of battery powered IEEE 802.11 compatible devices. This scheme is a synchronous approach. Time synchronization is achieved through periodically transmitting beacon frames which contain a copy of the beacon sender's time stamp (by contention in ad hoc mode and by the access point in infrastructure mode). Transmission time is therefore divided into so-called beacon intervals. At the start of each beacon interval, each station in the PS mode periodically wakes up for a duration known as ATIM Window. Stations that have data packets to transmit have to announce them first using a special control frame called the ATIM announcement frame. Backoff mechanism is used as collision resolution by calculating a random delay uniformly distributed between 0 and $2CW_{min}-1$ slots time and

wait for that delay time if transmission medium is detected as busy (CW_{min} is the minimum contention window size used in the backoff mechanism). The destination node will reply an ATIM ACK to the source node and both the source and destination will stay active for the entire beacon interval. After the ATIM window, the announced data packets will be transmitted using the basic DCF access procedure. Other stations that will not participate in the transmission can switch to the power saving mode again to save energy. Because even in the idle state, node still consumes significant amount of energy, about 20 times more than the power saving state according to the electronic specification in [5].

7.3.2 Application of the Battery Recovery Effect

In [124], the authors considered the battery package is composed of an array of L cells. The traditional method to drain power from cells connected in parallel is to discharge the same amount of current from all the cells. To transmit a packet, all the L cells are discharged for duration and the drained current of each cell is equal to $1/L$ of the required supply. They proposed a battery management mechanism by assigning one or more cells to supply the transmission power requirement on a per-packet basis while other cells can be in the idle state to recover their battery charge. They also introduced two scheduling mechanisms. The first technique is a random scheme, such that a job arrival is directed to each of the cells with probability equal to $1/L$, regardless of the number of packets Constituting the job. The second technique is the round robin scheduling, in which the job arrivals are directed to the cells by switching from a cell to the next one.

In [129], the authors propose such a routing mechanism BCRM, that enhances the network lifetime by letting some of the nodes recover part of their lost charge. This is done by putting the selected set of nodes to sleep. To implement BCRM, a node has to keep track of its charge consumption. When the charge in a node drops by c , it goes into sleep mode for a period t seconds in order to recovery $r\%$ of remaining capacity.

In [130], the authors proposed a routing protocol for wireless ad hoc network by using battery management metric in the routing decisions. They assume that nodes have the common maximum transmission range of ρ and R_i is the set of nodes that within node i 's transmission range. The energy consumed at node i (e_{ij}) to transmit a packet to node j is modeled as a function of the distance d_{ij} :

$$e_{ij} = \begin{cases} (\frac{d_{ij}}{\rho})^4, & \text{if } j \in R_i; \\ \infty, & \text{else.} \end{cases} \quad (\text{Eq. 7.1})$$

To represent the benefit of the recovery phenomenon, the battery status of a node is increased whenever the node's transmission rate is sufficiently low. They model the energy consumption at node i as a function of the transmission rate λ_i and of the mean energy necessary to node i to transmit a packet ($\bar{e}_i$). They indicate the energy increase function as $\Gamma(\lambda_i, \bar{e}_i)$ [122] with

$$\bar{e}_i = \frac{1}{R_i} \sum_{j \in R_i} e_i \quad (\text{Eq. 7.2})$$

So the current battery status b_i can be derived.

$$b_i = \begin{cases} b_i + \Gamma(\lambda_i, \bar{e}_i), & \text{if node } i \text{ is idle;} \\ b_i - [e_{ij} + \Phi(e_{ij} - e_{min})], & \text{else.} \end{cases} \quad (\text{Eq. 7.3})$$

Instead of a linear decrease of transmission energy, they use function Φ to compute the rate capacity effect based on current battery load. Then the routing algorithm assigns to each route a cost F_k . Given the source s and the destination g the cost function associated to the K^{th} route can be described as following:

$$F_k = \sum_{l_{ij} \in r_{sg}^k} [\Psi(\lambda_i) + p_{ij}] - \min_{i \in r_{sg}^k} b_i \quad (\text{Eq. 7.4})$$

in which l_{ij} is the link between nodes i and j belonging to route r_{sg}^k and Ψ is a function that emphasizes the source node.

Whenever the source has packets to transmit toward the destination, it evaluates the cost function for all the possible loop-free routes and selects the route such that:

$$F_m = \min_{r_{sg}^k} F_k \quad (\text{Eq. 7.5})$$

The route selected will take advantage of battery recovery to the maximum extent which prolong the battery lifetime.

7.4 Proposed Enhancement to PS Mode of IEEE 802.11 Protocol

According to [5], a typical wireless LAN card will consume distinctly different amount of energy in different operation states. Typically, the wireless network interface can operate in transmit state, receive state and idle state (any of these three states is considered as an active mode), or in power saving mode (also known as doze mode). The wireless interface is fully powered in active mode and is able to transmit and receive packets at any time or wait in idle state (although wireless interface consumes different amount of energy in each of these three states, it is significantly more than the energy in power saving mode). Furthermore the function in MAC protocol supported by physical layer design should be capable of switching the wireless interface in either the active or the doze mode at any time for the basic communication need.

Since the battery recovery effect occurs when battery load changes from a high to a low value, this effect can be utilized in IEEE 802.11 by intelligently adjusting the wireless LAN card in different operation states. The Idle and Doze states are considered as two levels of battery recovery periods, during which battery charge is slowly increased because of the battery recovery effect. The power consumption in idle state is significantly larger than that in the doze state, since the transceiver circuits are fully powered in the idle state. As a result, the idle state recovery is slower than that in the doze state.

In order to implement the intelligent battery utilization, the power state transition of IEEE 802.11 protocol has to be investigated. Figure 7.2 illustrates the power state transition of IEEE 802.11 protocol.

Figure 7.2: Operation state transition of IEEE 802.11 protocol

In IEEE 802.11 protocol, stations are in idle state when executing the exponential backoff mechanism to compete for the shared transmission medium or finished all pending transmission. The doze state is the result of the power state transition that utilized the power saving mode to save energy of mobiles. The basic principle in our proposed algorithm is to let the stations actively defer their transmission and stay in the battery recovery stage if they have detected that the batteries have been over charged (through monitoring the continuous battery discharging time and comparison with predefined threshold values).

Through this triggering information, stations can choose the following two mechanisms to actively recover their battery charge.

- Regeneration of the backoff counter with an exponentially increased contention window

The backoff counter decides the probability of winning the contention and the waiting time in idle state while multiple stations compete for the media. Through regeneration of the backoff counter with an exponentially increased contention window, stations can easily prolong the idle time that takes advantage of the recovery effect.

To be more specific, if a station has continuous transmitted k ($k \geq 6$) packets including the packet retransmission (which means the interval between each packet transmission is not longer than CW_{max} slots time), it can use the following procedure to actively differ the transmission to take advantage of the battery recovery effect.

$CW_{current}$, CW_{min} and CW_{max} are the station's current contention window size, minimum and maximum contention window size, respectively.

Algorithm 7.1: Algorithm for regeneration of backoff counter

```

1: if  $CW_{current}/CW_{min} \geq k$  then
2:   Use the current contention window  $CW_{current}$  without reset it to  $CW_{min}$  after a
   successful packet transmission for the  $(K + 1)^{th}$  packet
3: else
4:   if  $CW_{current} + CW_{min} \leq CW_{max}$  then
5:     Use  $(CW_{current} + CW_{min})$  as current contention window for the  $(K + 1)^{th}$  packet
6:   else
7:     Actively defer the transmission of  $(K + 1)^{th}$  packet for one beacon interval
8:     Reset  $CW_{current}$  to  $CW_{min}$ 
9:   end if
10: end if

```

- Longer time in the doze state through explicit piggyback information

If there are data packets buffered for transmission that have not been announced, stations can delay the ATIM announcement frames for desired doze recovery time (in number of beacon intervals). On the other hand, if a station has received ATIM frames destined for it while it intends to recover energy by stay in the doze state for the following beacon intervals, it can piggyback this information within the ATIM-ACK frame to reach an agreement of the transmission schedule.

7.5 Simulation Model and Results

In order to simulate our proposed algorithm as it is incorporated into existing IEEE 802.11 power saving mode, the well-known network simulator NS-2 [109] is used, which has a detailed simulation of the MAC/PHY layer characteristics of IEEE 802.11. Although NS-2 has the energy model based on the two-way ground radio propagation theory as well as the fading wireless channel, it can not correctly represent the battery behavior such as rate capacity effect and recovery effect. We utilize the runtime battery simulation model as introduced in [131], which is based on the Rakhmotov et al.'s mathematical description of the electrical and chemical processes inside a lithium-ion cell [132]. The mathematical presentation is easy to implement, however it is a fairly good close approximation since it has been validated by

comparing experimental results with the DUALFOIL battery simulator [133, 134]. Unlike the original energy model in NS-2 which is a linear function by calculating the discharged energy as product of the battery load and the duration of this load, the run-time battery model considers the battery discharge history and present battery load together to provide a more accurate and more realistic simulation of the battery behavior.

The runtime battery simulation model presented in 7.2 is described as the following pseudo code.

Algorithm 7.2: Algorithm for runtime battery simulation

```

1: PROGRAM Runtime Battery Simulation
2: GLOBALS:  $L_I$ ,  $S_t$ ,  $p$ ,  $\Delta$ ,  $\alpha$ ,  $\beta$ 
3: while Simulation is running do
4:   if  $discharge(l, t) > \alpha$  then
5:      $BatteryLifetime = SimulationTime$ 
6:     EXIT
7:   end if
8:    $BatteryLevel = discharge(l, t)/\alpha$ 
9: end while
10: FUNCTION:  $discharge(l, t)$ 
11: if  $l \neq L_p - 1$  then
12:    $L_p = 1$ 
13:   if  $t \neq 0$  then
14:      $S_p = t - \Delta$ 
15:   else
16:      $S_p = 0$ 
17:   Increment  $p$ 
18:   end if
19: end if
20:  $S_p = t$ 
21: if  $p = 1$  then
22:   RETURN  $2 \times L_0 \times A(t, t, 0, \beta)$ 
23: else
24:   RETURN  $\sum_{k=1}^p 2 \times L_{k-1} \times A(t, S_k, S_{k-1}, \beta)$ 
25: end if

```

In the simulation program, the battery model, which is on top of the NS-2 simulator, will periodically compute the energy consumption of each station. Based on the battery load changing history which is stored in a data structure (L_I) consisted of the battery load value

(L_t) and the time stamps (t) that indicate the duration of the battery discharge events with that specific load, the battery model can estimate the battery discharge at present time. If the cumulative discharge exceeds the capacity of the battery, the battery is fully discharged and node cannot participate in any data transmission. α and β are battery specific parameters. We set $\alpha = 35220$, $\beta = 0.637$, *voltage* = 4.1V which are the same as specified in [131]. The A function is part of the Rakhmotov et al.'s mathematical description of the electrical and chemical processes inside a lithium-ion cell which can be found in [132].

We consider the simulation scenario as the 2Mbps wireless LAN environment with stations within each other's transmission range. Stations consume 330mA, 240mA, 170mA and 15mA in the transmit, receive, idle and power saving mode, respectively. The power-on transition time is also consider 800 μ s, and during the transition time, a mobile station will consume twice the power than during the idle mode as similar simulation setup is also used in Section 3. The switching delays between active state and sleep state will prolong the delay of data packets and transition power is also an overhead to the protocol. However, since our protocol will put some over utilized nodes to doze state even for a beacon interval and utilize larger contention window to lower their priority in transmission, this part of overhead is considered to be nearly negligible. The simulation duration is 200s and the number of stations within the simulation area is varied to observe the impact to performance. Such scenarios are very similar to the situations when wireless LAN devices are used by many people in a large lecture theater or in the supermarket. We use randomly generated scenario files with different connection and traffic patterns and the results are the average values of 5 runs. Figure 7.3 shows the average energy consumption per packet which compares IEEE 802.11 power saving mode and our proposed enhancement. As the runtime battery model is adopted, our proposed algorithm which actively defers the transmission of data packets to take advantage of the battery recovery effect saves about 20% of the total energy consumption. As mentioned before, stations may expect longer additional delay when deferring their pending transmission to recover the battery charge. This

phenomenon is shown in Figure 7.4. However, since the additional delay is about 25% more than that of IEEE 802.11 power saving mode, in some applications such as web browsing it will not affect the performance as well as user's experience very much. At the same time, the network operation time is expected to be 20% more than that of IEEE 802.11.

Figure 7.3: Comparison of the energy consumption of IEEE 802.11 PSM and our proposed enhancement

Figure 7.4: Comparison of the average packet delay of IEEE 802.11 PSM and our proposed enhancement

7.6 Conclusion

In this chapter, an enhancement to the existing IEEE 802.11 power saving mode is presented. the runtime battery simulation model is incorporated into the NS-2 energy model. Based on the

modeling of battery recovery effect, a scheme that actively defers the data packet transmission is proposed to take advantage of the battery recovery effect. Based on the proposed enhancement to IEEE 802.11 that efficiently exploits the battery capacity, significant improvement of the battery lifetime can be achieved with the trade-off of only the minimum additional packet delay. However, in most of the services and applications that are not strictly time-critical, such as web browsing and sensor network, longer operation time is often preferred. Our proposed power efficient protocol, which can be easily incorporated to the existing power saving mode of IEEE 802.11, is ideally suitable for such applications.

Chapter 8

Conclusion and outline of future work

In this chapter, the conclusion of this thesis which covers our previous work of my Ph.D candidature will be addressed. The direction and technical area of the intended future work will also be given.

8.1 Our Contributions of the Research

Power efficient network protocols attract a lot of research interests in recent years, especially in the mobile communication environment. The intention of our research topic, "Power Efficient Mobile Ad Hoc Network", is to design the communication protocols with power efficiency as a major concern which will increase the operation time of battery-powered mobile communication devices. Our work during the Ph.D candidature can be summarized as follows.

- We have reviewed various types of typical communication protocols that have been proposed in MANET area, including the transportation layer protocols, multi-hop routing protocols and Medium Access Control layer protocols. This provides sufficient technical background to understand the operation characteristics and principles of MANET protocols. We reviewed the protocols which are designed for power efficiency or that consider energy consumption as an important performance metric. As the multiple access procedures that govern the access to the wireless medium have significant impact to the

power consumption, we therefore focus the attention on the research of power efficient MAC layer protocols. We survey the most typical power efficient MAC protocols used in MANET scenarios or some in the wireless communication field. Among all these MAC level approaches, IEEE 802.11 based wireless LAN is more promising as the standard of future wireless communication technology. We give extensive review of IEEE 802.11 Distributed Coordinated Function and the Power Saving mode that specified for it. This will help to understand our modification to 802.11 protocol that improve the energy saving and network performance.

- In this thesis, we propose modifications to IEEE 802.11 PS mode to reduce collision probability in the contention period and minimize the time that mobile stations have to stay in active state. Various scheduling mechanisms are proposed and discussed, which can provide a fair and power efficient service for all mobile stations. Probability of collision is greatly reduced through distributed traffic scheduling that insures the data transmission to be contention free. The proposed algorithm is more scalable when the number of mobile stations in an IBSS is increased. Furthermore, the traffic schedule minimizes the total time that mobile stations have to stay in the active state, which significantly reduce the energy consumption of mobile stations. The complexity and performance of the proposed algorithms are analyzed using simulation method and analytical models. The results show that the proposed algorithms performs better in reducing the total active time of all mobile stations and improve the network performance compared with original IEEE 802.11 protocol.
- Infrastructure based wireless LAN technology has also been widely used in today's personal communication environment. We propose a hybrid protocol which intelligently chooses the Access Point (AP) assisted DCF (Distributed Coordinator Function) and enhanced PCF (Point Coordinator Function) transmission mechanism of IEEE 802.11

protocol in an infrastructure based wireless LAN environment. We use Received Signal Strength Indicator (RSSI) method to estimate the distance between mobile stations and AP. Based on the estimation, mobile stations can efficiently communicate directly instead of being routed by access point if they are in the vicinity of each other. We also further extend this protocol by utilizing the historical end-to-end delay information to decide on the waking up time of mobile stations. The throughput is increased significantly due to the reduction of channel utilization through the direct transmission and waking up time estimation. The proposed protocol is a hybrid of AP assisted DCF and PCF operation, which is more flexible and fault-tolerant, and can be readily reverted to the traditional IEEE 802.11 protocol for compatible reason when required.

- Based on the observation that TSF plays an important role the IEEE 802.11 PS mode, we present a modification to the existing TSF for DCF by using different backoff counter range according to the clock accuracy of the stations. Using the proposed method, the probability of collision among beacons can be significantly reduced. This makes the proposed mechanism more scalable for large network. Furthermore, less time is required for the successful transmission of the beacon frames, which result in less energy consumption and high bandwidth utilization. In addition, the clocks can be converged quickly and a smaller clock deviation can be achieved compared with previous approaches. Simulation results show that there are significant improvements.
- Furthermore, we incorporate the runtime battery simulation model into the energy model of NS-2 simulator. Based on the modeling of battery recovery effect, we propose a scheme that actively defers the data packet transmission to take advantage of the battery recovery effect. Based on the proposed enhancement to IEEE 802.11 that efficiently exploits the battery capacity, significant improvement of the battery lifetime can be achieved with the trade-off of only the minimum additional packet delay. Our proposed power efficient

protocol, which can be easily incorporated to the existing power saving mode of IEEE 802.11, is ideally suitable for applications, such as web browsing and email which are not time-critical tasks.

8.2 Future Works

This section describes our intended future work.

8.2.1 Extension and Enhancement of Proposed Modification to IEEE 802.11

Based on our proposed modification to IEEE 802.11 standard described in chapter 3, there are some enhancements that can be investigated and implemented to achieve an even higher performance improvement or extend the existing protocol to be more flexible and adaptable.

- Packet scheduling in a multi-hop communication scenario.

As we have introduced before, IEEE 802.11 protocol assumes full connectivity within the IBSS. So mobile stations in a single IBSS are within each others' transmission range, which forms a single hop ad hoc communication situation. Actually, the power saving mode specified for IEEE 802.11 protocol is also not suitable for the multi-hop communication for the following reasons:

- (i) Lack of mechanism for global time synchronization.

The transmission of a beacon frame can be used to synchronize all hosts' beacon intervals only if it can be successfully received by all the stations within the IBSS. Otherwise, the ATIM windows cannot be common awake periods for all stations to exchange traffic announcement information. In a multi-hop MANET, clock synchronization is a non-trivial task compared with centralized infrastructure, because communication delays and mobility are unpredictable, especially when the network scale is large. IEEE 802.11 protocol also specified a PCF mode, which requires

the existence of an Access Point (or base station) acting as the point coordinator. In PCF mode, time synchronization is maintained by the AP. Several AP can be fully connected with each other through reliable communication links to form an extended service set, through which they can exchange time synchronization information. Synchronization can also be achieved if APs have access to external time services, such as NTP server or GPS, which are capable of providing precise synchronization service. But in the ad hoc communication scenario, without the centralized infrastructure, design the time synchronization for multi-hop communication will be very challenging. In chapter 6, we proposed a modified time synchronization procedure that achieves smaller clock deviation and more adaptive to the high mobile situation. Integration of these two protocols can be a promising direction to solve the synchronization problem.

(ii) Neighbor discovery.

A host can only realize the existence of its direct neighbor if it transmits radio signals. Incomplete or out-of-date neighbor information often leads to packet delivery error when routing layer protocols make the route decisions through neighbor information. This happens when the power state transition is used, however two neighboring stations may have non-overlapping awake period which makes them unable to communicate with each other. When transmission power adjustment is used, stations may choose the desired transmissions power which make the diversiform transmission ranges. That is why we have to investigate the neighbor discovery issues when power control mechanisms are applied to the multi-hop routing protocols.

(iii) Network partitioning.

Since stations tend to reduce the energy consumption by decrease the transmitted power, Network partitioning is often caused by the asymmetric transmission range. Some researches suggest using the highest transmission power to exchange so-called

”keep alive” control packets by one-hop broadcasting periodically. This is helpful in maintaining the connectivity and updating the neighbor information only when the network size and density is small. Otherwise it could turn out to be a hazardous situation when network is completely congested by the broadcast, since all nodes participate in the broadcast with highest transmission power.

- Integration of the proposed time synchronization protocols and modification of IEEE 802.11 power saving mode.

Mobile stations compete with each other within one hop using the procedure described in chapter 3 with ATIM window as the common awake period. Successful transmission of the ATIM frame follows by the transmission of the beacon immediately with p-persist method (separated by a inter-frame space of SIFS), if the specific node has not receive or send any beacon for as long as aBeaconInterval time. Other stations that have no ATIM announcement to transmit remain silence for a predefined duration every aBeaconInterval time to receive the beacon. The beacon will propagate as far as two hops from the beacon sender. Some nodes within two hops from the beacon sender will be selected as time rely agent randomly, which will join the beacon contention for the next beacon interval regardless of whether they have ATIM announcement to transmit. Each node will calculate the probability P as described in chapter 6 based on the comparison of the local timer and received beacon, to decide whether or not it will try to send the beacon for next beacon interval.

8.2.2 Integration of Transmission Power Control and Dynamic Power State Transition

Although there are a lot of proposals that try to achieve energy efficiency through power control or power state transition independently, little attention has been paid to combine the two approaches together seamlessly. However these two directions are not foreign to each other.

CHAPTER 8. CONCLUSION AND OUTLINE OF FUTURE WORK

Dynamic adjustment of transmission power according to the distance between the sender and receiver can be an effective way to avoid unnecessary power wastage and increase spatial reuse. The utilization of the power saving mode and the power state transition help mobile stations to conserve energy in idle state. However, in a heterogeneous network, variation of transmission power creates asymmetric wireless links between mobile stations. Furthermore, the absence of effective synchronization mechanism in a multi-hop environment often leads to asynchronous power state transition of mobile stations. These characteristics pose significant challenges to power efficient route discovery and maintenance as well as end-to-end packet delivery.

Power-aware routing protocols with power control dynamically adjust the transmission power according to the position of destination and try to break a single-hop long distance transmission into several small hops to achieve energy saving. Such kind of approaches is often referred as the topology control algorithm. However, as shown in Eq. Eq. 8.1, the fundamental basis for power control is based on the following formula:

Figure 8.1: Dynamic transmission power adjustment

$$D_1^k + D_2^k \ll (D_1 + D_2)^k, (k > 2, D_1, D_2 \gg 1) \quad (\text{Eq. 8.1})$$

where k is the path-loss exponent and is typically larger than 2. So shorter distance and small hops is often favorable in routing decision instead of long hop.

This approach has the inherent problem of not taking the power consumption of intermediate forwarding stations into consideration and measuring the energy consumption solely as the transmission power. The energy saved at the source station can be forfeit by the intermediate forwarding stations. So a new metric that takes the intermediate forwarding nodes into consideration has to be defined to provide more accurate information for routing decision.

The following issues has to be considered:

- The state transition from transmit mode to receive mode.

Although nodes operating in the transmit or receive mode are fully powered, the radio transmitter is working in different condition. Some researches have explored that the transmission and receiving modes will consume different amount of energy, but the time and energy consumption of the state transition have not been emphasized before.

- MAC control overhead

MAC level control overhead has to be considered, because it increases proportionally when the number of hops is increased. So the RTS and CTS packets exchanged prior each intermediate forwarding is not negligible. Furthermore the back-off mechanism used in 802.11 MAC is also a significant factor for two reasons:

- (i) The idle state contributes greatly to the total energy consumption, because node in idle state is fully powered and will monitor the channel status from time to time.
 - (ii) Using back-off mechanism will lead to the result that if two or more stations are competing to access the medium for their pending packets at about the same time, at least one station will have to wait the entire duration of the transmission of the others in idle state.
- Breaking the single long hop into several small hops will increase the probability of transmission failure through the hop-by-hop forwarding.
 - A large number of intermediate packet forwarding will definitely incur a longer packet delay.

So the trade-off between the power reduction and other performance metrics has to be investigated. In some scenarios, increase of the transmission power will help to heal the network partitioning and reduce the packet end-to-end delay. When the transmission power is increased,

the radio signal will cover a larger area. This inhibits some the stations within this range from simultaneous transmission. Then power state transition can take advantage in this situation to save energy of the stations that are in the backoff stage. On the other hand, when transmission power is reduced, the interference range is also reduced. Stations previously within interference range are now able to compete for the channel and they can switch to active state. Based on this theory, in chapter 5, we propose a hybrid protocol which intelligently chooses the Access Point (AP) assisted DCF (Distributed Coordinator Function) and enhanced PCF (Point Coordinator Function) transmission mechanism of IEEE 802.11 protocol in an infrastructure based wireless LAN environment. RSSI method is used to estimate the distance between mobile stations and AP. Based on the estimation, mobile stations can efficiently communicate directly instead of being routed by access point if they are in the vicinity of each other. This protocol is also further extended by utilizing the historical end-to-end delay information to decide the waking up time of mobile stations. The protocol utilizes transmission power control to intelligently communicate directly with peer mobile stations. The historical end-to-end delay information is employed to for dynamic power state transition of mobile stations. However the proposed protocol uses AP as the centralized coordinator. It will be very promising if transmission power control and power state transition can be integrated in an ad hoc environment, although it is very challenging to decide the timing and criteria for the power adjustment and state transition.

8.2.3 AP mobility

Implementation of IEEE 802.11 management functions in BSS and IBSS mode has been made possible as software components on normal mobile devices (e.g. Hostap). Through multi-hop mesh technology (e.g. Microsoft Mesh Network), AP is not necessarily required to be directly connected with the wired backbone, which means that AP itself can constantly move with or without predefined pattern. The impact of AP mobility on a heterogeneous network can be a very promising research area. The most obvious benefit of AP movement is that the transmission power of mobile stations to AP in their close vicinity can be reduced, which makes

it possible for AP to optimized power efficiency of mobile stations through traffic scheduling according to its own mobility.

8.2.4 Battery management in presence of multiple routes

In multi-hop MANET where the node density is sufficient, there normally exist multiple routes (Link-Disjoint or Node-Disjoint) between arbitrary source and destination pairs. Multiple routes can be used independently (in fault tolerant mode) or simultaneously (in load balance mode), however successful delivery of data packets depends on cooperation of all intermediate mobile stations along the route. Research on battery characteristics shows that the total energy delivered can be increased if battery cell is allowed to rest in between discharge periods owing to the diffusion mechanism. There are also online or offline scheduling mechanisms for optimal battery discharge. Selection of optimal battery discharge path in the presence of multiple routes is an effective way to prolong the life time of mobile stations and network connectivity.

8.2.5 Analytical Models for Multi-hop Networks

In chapter 4, we analyze the complexity and performance of different scheduling algorithms in our enhancement to IEEE 802.11 protocol using analytical model. However, the model is quite specific for the single-hop ad hoc communication scenario. Therefore, extending the model for a scenario with multi-hop communication scheduling is of great interest. In chapter 5, we compare the energy consumption of the routed transmission through AP and the direct transmission based on the distance between mobile stations and AP. Since we are not interested in the exact location of mobile stations, we do not use complex location system such as GPS or signal triangulation based approaches. However, the decision can be more accurate and efficient if stochastic model can be obtained from the historical signal strength information. We also present analysis and experimental results of end-to-end delay in a client-server communication scenario. This model can be further enhanced to be suitable for any communication scenario and provide a more accurate estimation of the waking up time of mobile stations.

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