An Efficient MAC Protocol for Improving Channel Efficiency and Power Efficiency in Wireless Ad Hoc Networks

Chun-Hung LIN

Department of Computer Science and Engineering
National Sun Yat-Sen University

lin@cse.nsysu.edu.tw

Chien-Yuan LIU

Department of Electronic Engineering
Cheng-Shiu University

cyliu@cc.csit.edu.tw

Abstract - Limited battery power is one of key constraints for continuous operation of mobile computers. The power consumption during data transmitting and receiving significantly depends on the MAC protocol of wireless networks. This paper presents a power saving distributed cycle stealing (PS-DCS) mechanism, which is used to enhance the IEEE 802.11 DCF MAC. The PS-DCS not only improves the wireless channel throughput of the IEEE 802.11 DCF. In addition, the PS-DCS saves a great amount of energy consumed by the operation of a standard 802.11 DCF. We illustrate the PS-DCS advantages via extensive simulation performed over wireless LAN. The results of simulation show that significant improvement on the throughput of wireless channel is obtained. Besides, the packet loss ratio and the packet mean delay time are also significantly reduced. Furthermore, the PS-DCS saves more than 70% power consumption of the IEEE 802.11 DCF operation.

1. Introduction

In recent years, the proliferation of portable computers and handheld devices has driven networks to support wireless connectivity [2] [11]. WLAN is one of essential technologies of wireless computer networks. In fact, WLAN has successfully adopted in many campus networks and enterprise networks. Basically wireless networks deliver much less bandwidth than wired networks, for example 1-11 Mbps of WLANs versus 10-100 Mbps of LANs. The media in wireless networks are shared and scarce resources. Thus, efficient utilization of a wireless transmission medium is an important issue [3] [5] [9].

Monks et al. [10] propose the power controlled media access (PCMA) protocol to improve the channel utilization of wireless media. The PCMA enables a greater number of simultaneous senders than the IEEE 802.11 MAC by adapting the transmission ranges to be the minimum value required to satisfy successful reception at the intended destination. Although, the PCMA enhances the throughput of wireless media, it also incurs more complicate communication networks. A single hop wireless network would become multi-hop wireless networks due to the transmission range is reduced to its minimum. Multiple smaller ranges of wireless networks are formed by the space fragmentation. Power adjustment is not only applied to medium access control of wireless ad hoc networks, but also affects the topology [13] [15] [16], the lifetime [2] [6] of wireless ad hoc networks.

Multi-hop wireless networks need a routing facility to find routes for delivering packets from the sources to the corresponding destinations. Perkins and Bhagwat [11] propose the destination-sequence distance-vector (DSDV) routing for multi-hop mobile ad hoc networks. The DSDV routing suffers from the propagation delay and the overhead of periodically updating its routing table. Perkins and Royer [12] [14] propose ad-hoc on-demand distance-vector (AODV) routing which eliminates global periodic routing updates in DSDV. However, route established latency and per-hop processing overhead is still unavoidable.

We investigate the issue of efficient channel utilization. Therefore, we propose a novel method, the PS-DCS mechanism, for enhancing the channel utilization of the IEEE 802.11 MAC. The PS-DCS adapts transmission range controlled medium access for spatial reuse purpose. In other words, all the communications should obey the power-distance constraints, which guarantee that all the transmissions would not disturb each other during all communication periods. This could enable simultaneous senders to issue their communications within the same period. We model the PS-DCS mechanism and simulate the communication behavior on randomly generated ad hoc networks. According to our simulations, the effect of enhancement is great and obvious.

The PS-DCS mechanism uses exact power level for transmitting the packet from the source station to the corresponding destination. Comparing to the full power transmission of standard IEEE 802.11 DCF MAC, the PS-DCS saves a large amount of energy consumed during the data communications. We developed a simulation model to calculate the power consumption of the

PS-DCS mechanism and that of the IEEE 802.11 DCF operation. We compare the performance of power utilization in three aspects. The first aspect is the aggregated energy consumed in both of the mechanisms. The second one is the energy efficiency derived from the results of simulation. The last aspect is the percentage energy saved by the PS-DCS mechanism. From all aspects, we assure the PS-DCS not only provides outstanding channel throughput, but also saves a huge amount of energy for data communications.

The remainder of the paper is organized as follows. In Section 2, we introduce the IEEE 802.11 DCF MAC standard to be applied on ad hoc networks. Section 3 describes the basic operations of the PS-DCS mechanism and its power-distance constraints. Section 4 describes our simulation and compares the results of experimental simulation of the PS-DCS mechanism to that of the IEEE 802.11 DCF MAC standard. Finally, we summarize the issue, the key results of the performance simulation and our future work in Section 5.

2. IEEE 802.11 Ad Hoc Networks

The IEEE 802.11 specification includes MAC layer and physical layer. This paper only addresses to the MAC layer portion. Aad et al. [1] [5] [7] [8] introduces the IEEE 802.11 standard with more widespread descriptions. The detailed description is described in the ANSI/IEEE standard [17]. We briefly introduce the terms defined in IEEE 802.11 standard.

A Wireless Medium (WM) is the medium used to implement the transfer of protocol data units (PDUs) between peer physical layer (PHY) entities of a WLAN. A Station (STA) is any device that contains an IEEE 802.11 conformant MAC and PHY interface to the WM. STAs working in either distributed coordination function (DCF) or point coordination function (PCF) form a basic service set (BSS). The BSS covered area is called the basic service area (BSA). A BSS can either be an infrastructure network or an independent ad hoc network.

An ad hoc network composed solely of stations within mutual communication range of each other via the WM. An ad hoc network is typically created in a spontaneous manner. The principal distinguishing characteristic of an ad hoc network is its limited temporal and spatial extent. These limitations allow the act of creating and dissolving the ad hoc network to be sufficiently straightforward and convenient so as to be achievable by non-technical users of the network facilities; i.e., no specialized technical skills are required and little or no investment of time or additional resources is required beyond the stations that are to participate in the ad hoc network.

There are two service control methods specified in the IEEE 802.11 MAC standard. One is the PCF and the other one is the DCF. The DCF provides contention based service, whereas the PCF provides a contention free service. However, DCF is the only service provided in an ad hoc network. Therefore, we only focus on the DCF control function in this paper. The DCF supports delay insensitive data transmission, and works in contention mode. The IEEE 802.11 DCF adopts carrier sense multiple access (CSMA) / collision avoidance (CA) scheme. The hidden terminal problem [2] implies a collision is possible to happen while multiple hidden STAs try to transmit their packets after the channel to become idle. To avoid collision, the IEEE 802.11 adopts a binary exponential back-off scheme. The binary exponential back-off scheme is implemented by each station by means of a parameter, named back-off counter, which maintains the number of empty slots the tagging STA must observe on the channel before performing its own transmission attempt. When the tagging STA needs to schedule a new transmission, it selects a particular slot among those of the contention window, whose size is maintained in a MAC preset parameter CW_min. The back-off value is defined by the following expression:

$$Backoff\_Counter(rt\_att) =$$

$$\left\lfloor \left\{ rand() \times \min\left[CW\_max,\, CW\_min \times 2^{\,rt\_att} \right] \right\} \right\rfloor$$

Where CW_max is a MAC preset parameter, rand() is a function which returns pseudo random number uniformly distributed in [0..1], and rt_att is the number of retransmission attempt with initial value one. After each unsuccessful transmission, the rt_att is incremented by one. The STA doubles the contention window size until it reaches the CW_max. The increasing of the contention window size is the reaction that the IEEE 802.11 DCF provides to react to a congestion condition and to make the access adaptive to channel conditions.

The back-off counter is decreased as long as an idle slot is sensed, it is frozen when a transmission is detected, and reactivated after the channel is become idle for at least a DIFS time. While the back-off counter reaches the value zero, the STA can transmit its data frame. If the transmission generates a collision, the size of contention window is doubled for next retransmission attempt to reduce the contention of the medium.

A RTS/CTS scheme is added to relieve the hidden terminal problem of the basic CSMA/CA scheme. A RTS is sent before a PDU transmission. If collision happens, the wasted channel time is only 20 octets instead of a full PDU length. A CTS is replied by a destination if it is ready to receive a PDU. When the source receives the CTS, it starts transmitting its PDU. All other STAs update their network allocation vector (NAV) whenever they hear a RTS, a CTS, or a PDU frame. The handshake-timing diagram of RTS/CTS/DATA/ACK, SIFS/DIFS, and NAV is shown in Figure 1.

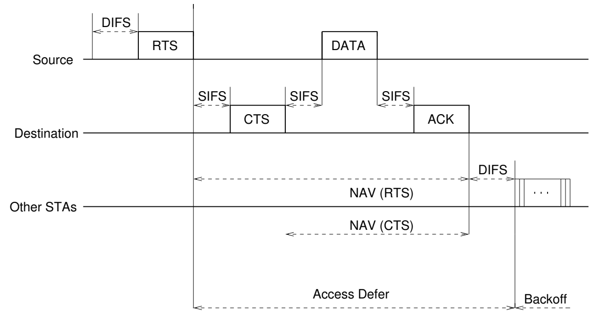

Figure 1: The DCF timing of a PDU transmission

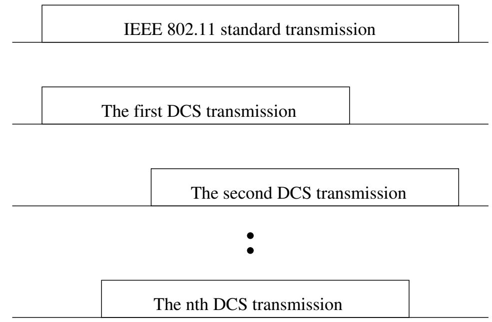

Figure 2: Multiple frames transmitted in PS-DCS mechanism

A source has to wait at least DCF Inter Frame Spacing (DIFS) time and an additional random back-off time after the channel is idle to avoid collision. Short ISF (SIFS) is shorter than DIFS. This is a simple prioritized scheme to let an ACK frame, a CTS frame, or a PDU frame has higher priority than a RTS frame.

3. PS-DCS Mechanism

In an IEEE 802.11 ad hoc network without power control of wireless transmission, the source radio interface always transmits a frame with the maximum power level. Recent researches [10], [15] indicate full power transmission not only consuming extra energy but also unfavorable to channel spatial reuse.

We assume all stations (STAs) in the ad hoc network have idea power control capability. [18] depicted the required transmission power is a function of the distance between a source and a destination. The PCMA [8] also generalized the collision avoidance to power control model instead of on/off model. The PCMA demonstrated that a greater number of senders were allowed than IEEE 802.11 by adapting the transmission ranges to be the minimum value required to satisfy successful reception at the intended destination.

Based on power controlled transmission, a source can control its transmission range to be the minimum requirement to reach its destination. The STAs outside the affected range of the current communication of the source-destination pair may have chances to transmit their data frame via the wireless communication channel. Since these unaffected STAs could transmit their frame concurrently if they do not violate the power-transmission range constraints. It seems like a DMA transmission steals cycle from a CPU, meanwhile both of the DMA data movement and the CPU computation can execute at the same duration. Each unaffected STA executes the cycle stealing mechanism in distributed way. Thus, we name the mechanism as distributed cycle stealing (DCS).

Figure 2 shows an example of the PS-DCS concurrent transmissions. At very beginning of an IEEE 802.11 standard transmission, a source STA issues a RTS frame with full power to inform an intended destination STA and all neighboring STAs. All other STAs, including the corresponding destination STA, listen to the RTS frame and record access control related data of the frame in their MAC table for later power-transmission range constraints calculation. The MAC related data includes the source id, destination id, the distance from the source to the STA, and the required transmission period of the following data frame. From [4,18], the signal strength drops proportional to the distance to the nth power. Therefore, we can calculate the distance value by the amount of signal attenuation, which is the difference between the maximum source transmission signal level and the received signal strength.

The destination STA then replies a CTS frame with full transmission power to inform its source STA, meanwhile to inform its neighbors for relieving hidden terminal problem. The reply frame also includes the source id, destination id, the distance from the source to the destination which is calculated from the amount of signal attenuation, and the period of the following data communication which is copied from the RTS frame. If the source STA received the replied CTS successfully, it starts a data frame transmission with exact power calculated from the signal-distance relation function. All the others STA, located outside the covered ranges of the source STA and the destination STA, are able to issue their communications if (I) they need to send data packets waiting in their buffers, (II) the newer communications are not interfering with the primary communication, (III) and the newer communications are not interfering with each other. In this way, the PS-DCS not only enables the possibility of spatial reuse, but also saves power of the source STA.

The covered ranges of concurrent power controlled communications are depicted in Figure 3. Any STAs outside the covered ranges are also allowed to communicate, if they do not violate the non-overlap distance constraints. Let assume that S and D are the source STA and the destination STA of the first communication. S' and D' are the source STA and the destination STA of the second communication. S'' and D'' are the source STA and the destination STA of the third communication. Dist () is a distance function for calculating the distance between any two STAs in the ad hoc network. The non-overlap distance constraints are described as follows.

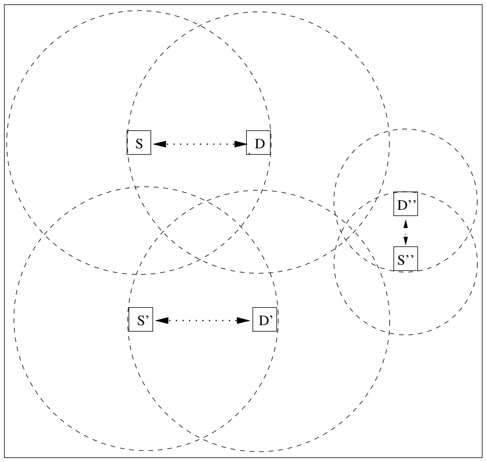

Figure 3: The covered ranges of concurrent communications

$$Min[dist(S, S^{'}), dist(S, D^{'}), dist(D, S^{'}), dist(D, D^{'})]$$

$$> Min[dist(S, D), dist(S^{'}, D^{'})] \quad (1)$$

$$Min[dist(S, S^{''}), dist(S, D^{''}), dist(D, S^{''}), dist(D, D^{''})]$$

$$> Min[dist(S, D), dist(S^{''}, D^{''})] \quad (2)$$

$$Min[dist(S^{'}, S^{''}), dist(S^{'}, D^{''}), dist(D^{'} \cdot S^{''}), dist(D^{'}, D^{''})]$$

$$> Min[dist(S^{'}, D^{'}), dist(S^{''}, D^{''})] \quad (3)$$

The first communication and the second communication are not overlapped and are not affected by each other, if unequal equation (1) is hold. Furthermore, if unequal equation (2) is established, the first communication and the third communication are not overlapped and are not affected by each other. In the same way, the second communication and the third communication can transmit at the same time, if unequal equation (3) is true. While all the unequal equations (1) to (3) are satisfied, we can assert that all three communications can deliver their PDU frames concurrently. Therefore, the packet delivery ratio of the ad hoc network is enhanced. Meanwhile, PS-DCS has an effect to empty the buffers of $S^{'}$ and $S^{''}$ of the above example by early delivering the waiting PDU frames of $S^{'}$ and $S^{''}$. In addition, PS-DCS contributes to decrease the packets waiting time in the corresponding waiting queues. Therefore, the mean end to end delay time of all transmitted packets is shortened. Next section explained these improvements by the results of performance simulations.

Although the DCS mechanism enables multiple simultaneous transmissions within the period of the primary IEEE 802.11 transmission, all the stealing-period transmissions have to end up their communications before the end of the primary communication. The timing constraint is caused by the following two considerations. The first reason is for compatible to IEEE 802.11 DCF standard. At the end of the primary transmission, all STAs have to listen to the wireless channel again. They have to compete for channel access after the channel is idle for a DIFS period. If there are some STAs still under communication, the IEEE 802.11 DCF would not work accordingly. Therefore, unpredictable collisions may happen. Thus, more retransmission times, extra energy wastage, and greater delivery delay time would be unavoidable. The second consideration is not to complicate the single hop ad hoc network. If some STAs prolong their communications after they stole cycles from the primary communication period, the single-hop ad hoc network becomes multiple small communication networks which are not our expectation.

4. Simulation Experiments

To measure the effectiveness of the PS-DCS mechanism, we simulate the PS-DCS on many randomly generated topologies. Each topology has 50 nodes, which is generated randomly, in a square region. Nodes in the simulation have radios with 1Mbps bandwidth and can ideally control their transmission range by varying their radio power level. We do not simulate the ad hoc network with mobility. At current simulation, we plan to discover the contributions of the PS-DCS mechanism to a static ad hoc network in comparing to that of IEEE 802.11 standard DCF MAC. We consider to do further simulation including mobility and other factors in future. We simulate different traffic load by adjusting the mean packet inter-arrival time. Shorter mean packet inter-arrival time represents heavier traffic load. In contrast, longer mean packet inter-arrival time represents lighter traffic load. Packets are generated with random sizes at random nodes. Each packet length ranges from 64 bytes to 1024 bytes. 200 network topologies are simulated for each of traffic load in order to have a smooth results. Table 1 lists all simulation parameters and their setting values.

Table 1: Simulation parameters setting

Parameter type	Parameter value
Network dimension	1×1
# of nodes	50
Channel bandwidth	1 Mbps
Packet length	64 - 1024 bytes
Mean packet arrival time	2.88 - 5.76 mS
Topologies	200
Simulation time	300 S
Slot time	50 uS
RTS	20 bytes
CTS, ACK	14 bytes
DIFS	128 uS
SIFS	28 uS

The simulations are divided into two parts. One is the measurement of the bandwidth improvement of the

PS-DCS mechanism to that of the IEEE 802.11 DCF MAC. The results of bandwidth simulation is described in Section 4.1. The other one is to measure the power saving effect of the PS-DCS mechanism in comparing to that of the standard IEEE 802.11 DCF MAC. Section 4.2 illustrates the power saving results in detail.

4.1 Bandwidth Simulation

Figure 4 shows packet delivery ratio versus traffic load in mean packet inter-arrival time. The packet delivery ratio is the ratio of the number of all successful transmitted data packets to the number of all generated data packets. In case of light traffic load, almost all packets can be delivered through the air. Packet delivery ratio gradually decreased as traffic load increased. The PS-DCS sustained heavier traffic load than IEEE 802.11 DCF. When mean packet inter-arrival time was at 4.5 mini seconds, packet delivery ratio of IEEE 802.11 DCF was near 86 percent, whereas PS-DCS still maintained more than 96 percent packet delivery ratio. The packet delivery ratio drops sharply while the traffic load is higher than that of 4.5 ms of the mean packet inter-arrival time. As for heavy traffic load case, e.g. when mean packet inter-arrival time was at 3.5 mini seconds, packet delivery ratio of IEEE 802.11 DCF heavily dropped down to 68 percent, whereas PS-DCS still kept its packet delivery ratio above 76 percent. The greatest improvement of packet delivery ratio by using DCS was up to 11 percent in comparing to that of the standard IEEE 802.11 DCF.

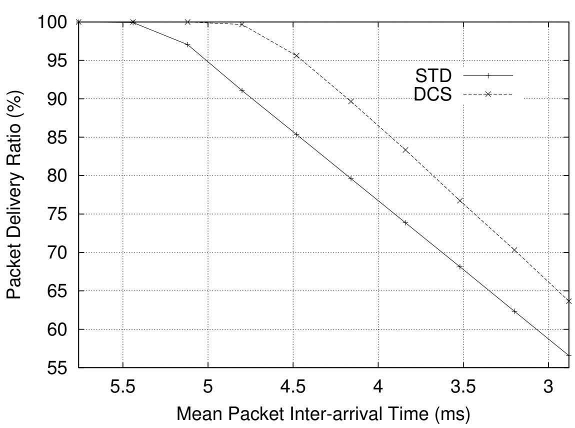

Figure 4: Throughput comparison of IEEE 802.11 DCF and PS-DCS

Packet loss ratio is the ratio of the number of all lost data packets to the number of all generated data packets. In Figure 5, we illustrate the simulation results of packet loss ratio of the IEEE 802.11 DCF and that of the PS-DCS. In very light load case, e.g. when mean packet inter-arrival time is greater than 5.5 ms, both of the IEEE 802.11 DCF and the PS-DCS have zero packet loss. That means all packets generated at each node are successfully delivered to the destination node without any loss. While traffic load becomes heavier, the packet loss ratio is increased, too. For example, when mean packet inter-arrival time is at 4.8 ms, the IEEE 802.11 DCF generates about 8 percent packet loss ratio, whereas the PS-DCS sustains the traffic load and still generates near zero percent packet loss ratio. In case of heavy load, such as mean packet inter-arrival time is at 4.5 ms, the IEEE 802.11 DCF already generates near 15 percent packet loss ratio. In contrast, the PS-DCS only generates less than 5 percent packet loss ratio.

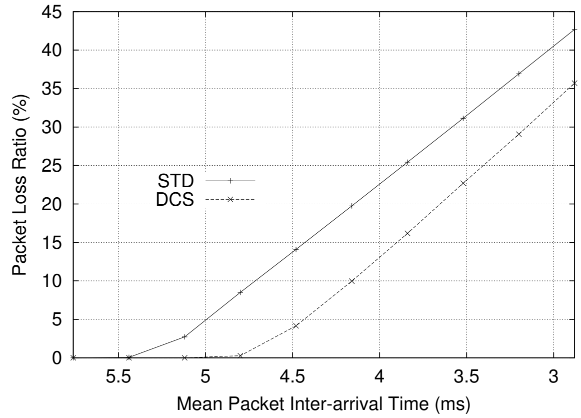

Figure 5: Packet loss ratio comparison of IEEE 802.11 DCF and PS-DCS

Figure 6 illustrates the mean packet latency time of the IEEE 802.11 DCF and that of the PS-DCS. From Figure 6, we know that the PS-DCS apparently shortened mean packet delay time in all cases, especially in heavy load situation. For example at mean packet inter-arrival time was at 3.5 ms, the IEEE 802.11 DCF causes about 3.2 seconds of mean packet delay time, whereas PS-DCS causes only 2.2 seconds. The improvement is up to 30 percent reduction of the mean packet latency time. In the growing multimedia transmission and real-time application of wireless communications the enhancement of the packet latency time has a great benefit for accelerating the response time and for guaranteeing the faster interaction of these kinds of applications.

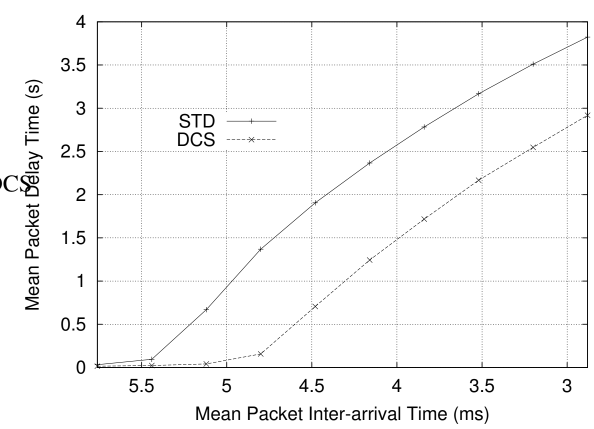

Figure 6: packet latency time of IEEE 802.11 DCF and PS-DCS

We describe the DCS ratio in Figure 7. We define the DCS ratio as the ratio of the number of all the stolen data packets, which is transmitted by using the PS-DCS mechanism, to the number of all generated data packets. The best DCS ratio occurs at mean packet inter-arrival time equal to 4.5 ms. We earn more than 13 percent of the generated data packets, which should be waiting in the buffers of the corresponding STAs according to the IEEE 802.11 DCF and now are sent by using the PS-DCS mechanism. In case of very light traffi c load, DCS ratio merely contributes a small percentage. This is because most of data packets are sent immediately after these packets arrived at the corresponding STAs. There are only a few packets queued in the STAs. Therefore the PS-DCS does not help much for the light traffi c load. When the traffi c load becomes very heavy, the DCS ratio is gradually decreasing. The reason is that over saturated traffi c load causes a great amount of packet loss and collisions. When this happens, the PS-DCS can still relieve the packet loss ratio as depicted in Figure 5. In most of applications, however, this heavy load situation should be avoided. Because the quality of service would be totally unacceptable, while the packet throughput is already less than 70 percent of packet delivery as illustrated in Figure 4.

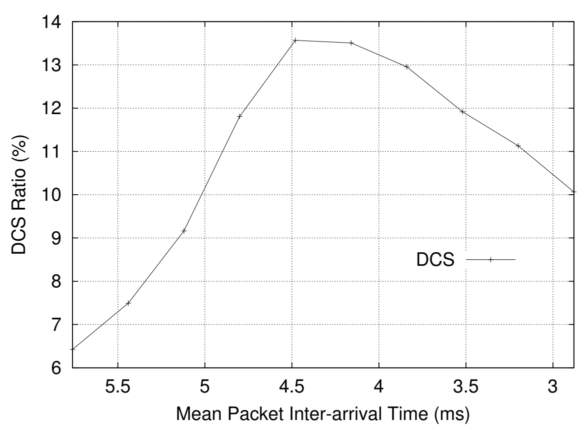

Figure 7: DCS ratio versus traffi c load

The bandwidth effi ciency is defi ned as total transmitted data bits divided by total simulation time in micro second. Figure 8 shows the bandwidth effi ciency of the PS-DCS and that of the standard IEEE 802.11 DCF. In case of light load, both of bandwidth effi ciency are lower than 0.8 bits per second. This is because there is less data packets waiting for transmission. Therefore, the channel idle existed sometimes during whole simulation period. The bandwidth effi ciency is increasing as the traffi c load becomes heavier. However, the standard 802.11 DCF reaches a saturation value of 0.82 bits per micro second. Thereafter, it decreases slightly as the traffi c load increases. The reason of this situation is that more packet arrivals cause more collisions, which waste channel bandwidth. In contrast, the PS-DCS mechanism still keep its bandwidth effi ciency in increasing until it reaches a higher saturation value of greater than 0.92 bits per mocro second. In our simulation, the maximum channel bandwidth is 1.0 bits per micro second. The PS-DCS mechanism performs very close to the upmost value of the channel bandwidth.

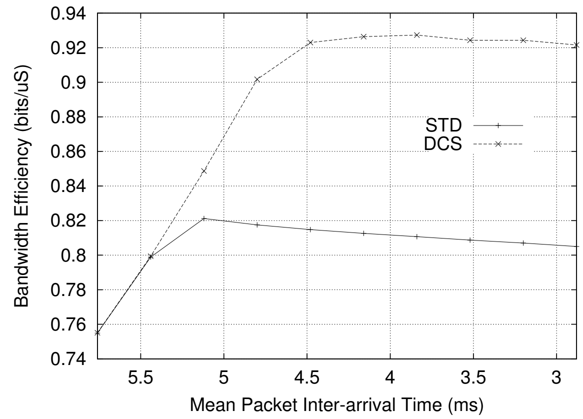

Figure 8: Bandwidth effi ciency versus traffi c load

We summarize the bandwidth simulation as follows. The PS-DCS tries stolen cycles to transmit more packets than that of the standard IEEE 802.11 DCF. Therefore, the PS-DCS mechanism has higher packet throughput, lower packet loss ratio, lower mean packet delay time, and much better bandwidth effi ciency.

4.2 Power Simulation

Figure 9 depicts the aggregated energy consumed during whole simulation period. In Figure 9, the standard IEEE 802.11 DCF operation consumes about a value higher than 15000 Joule (J) for all traffi c load cases. This is because all stations beside the sender and the receiver are stayed in receiving state. Although, power saving mode is designed in the IEEE 802.11 MAC. It is only defi ned for PCF operation. To support power saving DCF operation, further extension to the standard is required. It is out of scope of this paper.

The aggregated energy consumption of the PS-DCS mechanism is slightly higher than 4000J. The PS-DCS mechanism enables all stations to calculate the distance from the senders and the receivers to themselves. They also control their power level while they can steal cycle to send their data packet concurrently. A station goes into sleep mode if it detects itself is covered by a certain sender or receiver. Since each communication covers the region of the union of the circles, which centered with the sender and the receiver. All covered stations within the union range save their power by going to sleep. Simulation result shows that the PS-DCS saves a great amount power than that of the IEEE 802.11 DCF.

Figure 10 illustrates that more than seventy percent of power is saved in the PS-DCS operation. The PS-DCS even saves more power while the traffi c load becomes heavier. The reason is that higher traffi c generates more data packets and causes higher dcs ratio as Figure 7. This implies more regions are covered by the communications. Thus, more stations are going to sleep during the corresponding periods of communications.

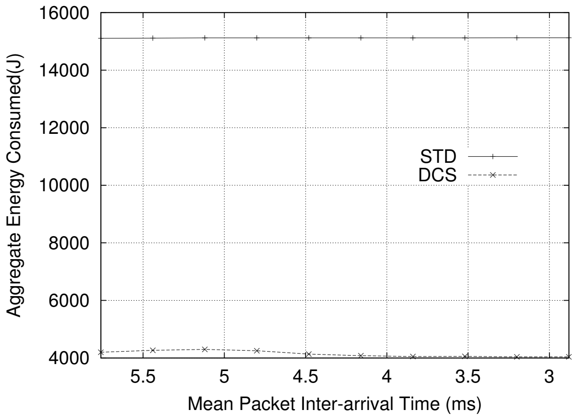

Figure 9: Aggregated energy consumed versus traffi c load

Therefore, the PS-DCS operation saves more energy. Figure 10 shows more than 70 percentage of power consumption is saved by the PS-DCS. In other words, all stations can operate three times longer than that of standard IEEE 802.11 DCF.

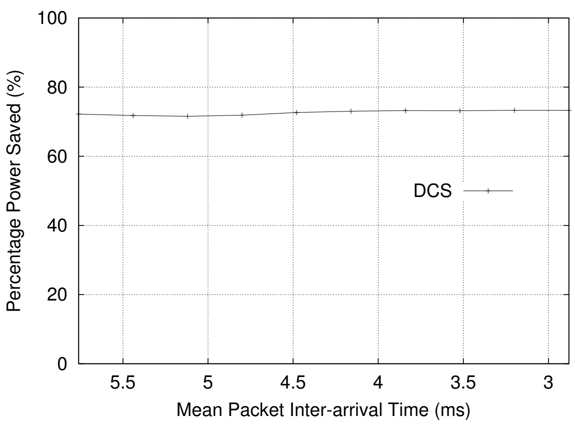

Figure 10: Percentage power saved versus traffi c load

Finally, we describe the energy effi ciency obtained from both of mechanisms. The energy effi ciency is defi ned as total transmitted data bits divided by total energy consumed during whole simulation period. Figure 11 shows that the energy effi ciency of the PS-DCS is much higher than that of the IEEE 802.11 DCF. Because the PS-DCS transmits more data packets than the IEEE 802.11 DCF. Moreover, the PS-DCS saves a great amount of energy in comparing to that of the IEEE 802.11 DCF. Therefore, the PS-DCS achieves much better energy effi ciency. In light load case, it provides near four times of energy effi ciency of the IEEE 802.11 DCF. In heavy load case, it performs in higher energy effi - ciency. For example, at 3 ms of the mean packet interarrival time, the energy effi ciency of the PS-DCS is near 0.07 bits per micro Joule, whereas the IEEE 802.11 DCF provides only 0.016 bits per micro Joule.

We summarize the power simulation as follows. The PS-DCS saves more energy by setting more covered stations into sleep state. Combining the bandwidth enhancement, the PS-DCS achieves much higher energy effi ciency than that of the standard IEEE 802.11 DCF.

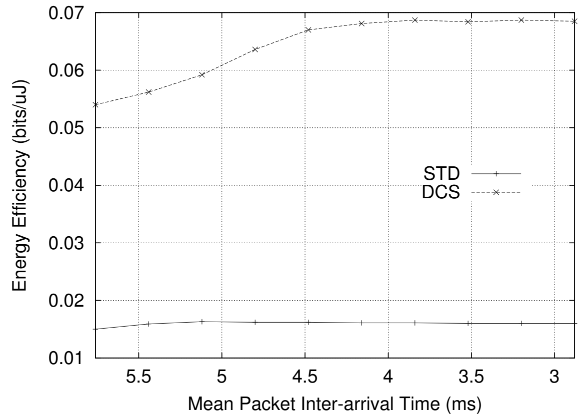

Figure 11: Energy effi ciency versus traffi c load

5. Conclusions

WLAN is widely adopted in many applications, such as the enterprise and campus wireless networks. This is because WALN is easy to install and is flexible to sharp its topologies. However, WLAN provides a very limited bandwidth and battery power in comparing to that of wired LAN. Therefore, effi cient utilization of wireless bandwidth and the energy performance of access control appear more important.

We propose a novel mechanism- the PS-DCS to improve the performance of the IEEE 802.11 DCF MAC. The PS-DCS reuse the network space by applying power control on the radio interface of each station. In addition, the PS-DCS steal cycles for concurrent transmissions from the primary 802.11 communication period. To prove our method, we designed and developed a simulation model to investigate the behavior of the PS-DCS mechanism. Simulation experiments are performed in randomly generated topologies over varying traffi c load. We measure the required data for the calculation of the packet delivery ratio, the packet loss ratio, the mean packet delay time, the DCS ratio , the bandwidth effi ciency, the aggregated energy consumption, the percentage power saved, and the energy effi - ciency versus varying traffi c load which is represented by different mean packet inter-arrival time.

From the results of simulation, we confi rm that the PS-DCS obviously improves the packet delivery ratio up to 11 percent than that of standard IEEE 802.11 DCF. Furthermore, the PS-DCS signifi cantly decreases the packet loss ratio and the packet delivery latency. In addition, the PS-DCS also saves a huge amount of energy consumption. More than 70 percent of power is saved according to the simulation results. The energy effi ciency is enhanced up to four times than that of the standard IEEE 802.11 DCF.

Finally, we are working to develop an analytical model of the PS-DCS mechanism in order to strengthen the results of our experimental simulations.

References

[1] I. Aad and C. Castelluccia, "Differentiation mechanisms for IEEE 802.11," *Proceedings of IEEE INFOCOM 2001,* pp.209-218, vol.1.

[2] V. Bharghavan, A. Demers, S. Shenker and Lixia Zhang, "MACAW: A Media Access Protocol for Wireless LAN's," *Proceedings of SIGCOMM 94,* pp.212-225.

[3] L. Bononi, M. Conti and L. Donatiello, "Design and performance evaluation of a distributed contention control (DCC) mechanism for IEEE 802.11 wireless local area networks," *Proceedings of WOWMOM 1998,* pp.59-67.

[4] L. Bononi, M. Conti and L. Donatiello, "A distributed mechanism for power saving in IEEE 802.11 wireless LANs," *ACM J. Mobile Networks and Applications,* vol. 6, pp.211-222, 2001.

[5] F. Cali, M. Conti and E. Gregori, "IEEE 802.11 protocol: design and performance evaluation of an adaptive backoff mechanism," *IEEE journal on selected areas in communications,* vol. 18, no. 9, September 2000.

[6] J.-H. Chang and L. Tassiulas, "Energy consering routing in wireless ad-hoc networks," *Proceedings of IEEE INFOCOM 2000.*

[7] B.P. Crow, I. Widjaja, J.G. Kim, and P.T. Sakai, "IEEE 802.11 wireless local area networks," *IEEE Communication Magazine,* September 1997.

[8] A. Ganz, A. Phonphoem, and Z. Gaze, "Robust superpoll with chaining protocol for IEEE 802.11 wireless LANs in support of multimedia applications," *ACM Wireless Networks,* vol. 7, pp.65-73, 2001.

[9] V. Kanodia, C. Li, A Sabharwal, B.Sadeghi, and E. Knightly, "Distributed multi-hop scheduling and medium access with delay and throughput constraints," *Proceedings of ACM SIGMOBILE 2001,* pp.200-209.

[10] J.P. Monks and V. Bharghavan and W.-M.W. Hwu, "A Power Controlled Multiple Access Protocol for Wireless Packet Networks," *Proceedings of IEEE INFOCOM 2001.*

[11] C.E. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers," *Proceedings of SIGCOMM 94,* pp.234-244.

[12] C.E. Perkins and E.M. Royer, "Ad-hoc on-demand distance vector routing," *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systerns and Applications,* pages 90-100, New Orleans, LA, February 1999.

[13] R. Ramanathan and R. Rosales-Hain, "Topology control of multiple wireless networks using transmit power control adjustment," *Proceedings of IEEE INFOCOM 2000.*

[14] E.M. Royer and C.E. Perkins, "Transmission Range Effects on AODV Multicast," *ACM J. Mobile Networks and Applications,* 2000.

[15] S. Singh and C.S. Raghavendra, "PAMAS- power aware multi-access protocol with signaling for ad hoc networks," *ACM Computer Communication Review,* pp. 5-26, July 1998.

[16] R. Wattenhofer, L. Li, P. Bahl, and Y.-M. Wang, "Distributed topology control for power efficient operation in multihop wireless ad hoc networks," *Proceedings of INFOCOM 2001.*

[17] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *ANSI/IEEE Standard 802.11, Part 11,* 1999 Edition

[18] W.L. Stutzman and G.A. Thiele, "Antenna Theory and Design," *John Wiley & Sons,* 1998.