Opportunistic Packet Scheduling over IEEE 802.11 WLAN

Sung Won Kim

School of Electrical Engineering and Computer Science, Yeungnam University, Gyeongsangbuk-do, 712-749, Korea
ksw@ieee.org

Abstract. This paper introduces an opportunistic packet scheduling method and medium access control (MAC) scheme for controlling the throughput in wireless local area networks (WLANs). The proposed method takes advantage of the multi-user diversity in time-varying wireless channel while the asymmetric traffic load problem between the uplink and the downlink is alleviated. The proposed method can be implemented without the modification of the deployed IEEE 802.11 nodes. The performance of the proposed method is compared with IEEE 802.11 Distributed Coordination Function (DCF) by computer simulations.

1 Introduction

Medium Access Control (MAC) protocol in the IEEE 802.11 standard [1] consists of two coordination functions: mandatory Distributed Coordination Function (DCF) and optional Point Coordination Function (PCF). In the DCF, a set of wireless nodes communicates with each other using a contention-based channel access method, namely Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CA is known for its inherent fairness between nodes and robustness. It is quite effective in supporting symmetric traffic loads in ad hoc networks where the traffic loads between nodes are similar.

For infrastructure wireless local area network (WLAN) applications such as hotspots [2]–[4], the system consists of N users communicating to a common entity (e.g., an access point, AP). The nature of independent time-varying channels across different users in a multi-user wireless system provides multi-user diversity. This particular form of diversity could be exploited by tracking the channel fluctuations between each user and the AP, and scheduling transmissions to users when their instantaneous channel quality is near maximum. It is observed that the probability of successful packet transfer increases significantly when the channel state information is exploited opportunistically [5].

Opportunistic scheduling, used to extract multi-user diversity gain, was first proposed in [6] and then extended to many wireless communication systems [7]. An opportunistic scheduling algorithm that exploits the inherent multi-user diversity has been implemented as the standard algorithm in the third-generation cellular system IS-856 [8] (also known as high data rate, HDR). To enable the opportunistic multi-user communications, timely channel information of each

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link is required for an effective scheduling. Just as all the previous schemes have assumed, the exploitation of timely channel information is possible in cellular networks where the base station acts as a central controller and control channels are available for channel state feedback.

It is difficult to utilize the multi-user diversity in WLANs. The AP cannot track the channel fluctuations of each link because of the single shared medium and the distributed CSMA/CA MAC protocol. The opportunistic packet scheduling methods for WLANs are presented in [9]–[11]. The key mechanism of the method is the use of multicast RTS (Request-To-Send) and priority-based CTS (Clear-To-Send) to probe the channel status information. Since their methods require the modification of RTS and CTS in the standard, the scheme cannot be directly applied into widely deployed IEEE 802.11 typed WLANs.

On the other hand, this form of the multi-user wireless system produces asymmetric traffic loads where most of the traffic loads converge into the AP. For example, Internet access or mobile computing uses transmission control protocol (TCP) or user datagram protocol (UDP) in which the offered traffic load is strongly biased toward the downlink (from AP to nodes) against the uplink (from nodes to AP) or the direct link (from nodes to nodes). Thus, these traffic flows for the downlink are completely blocked due to the CSMA/CA MAC protocol in distributed environments.

In this paper, we propose an enhanced WLAN MAC protocol which alleviates the bottleneck problem by using the opportunistic packet scheduling. The remainder of this paper is organized as follows. The next section reviews the background of the IEEE 802.11 system operation. Section 3 describes the proposed method. In Section 4, we investigate the enhancement of the proposed method with some numerical results. Finally, the paper is concluded in Section 5.

2 Background

2.1 Review of IEEE 802.11 DCF

The DCF achieves automatic medium sharing between compatible nodes through the use of CSMA/CA. Before initiating a transmission, a node senses the channel to determine whether or not another node is transmitting. If the medium is sensed idle for a specified time interval, called the distributed interframe space (DIFS), the node is allowed to transmit. If the medium is sensed busy, the transmission is deferred until the ongoing transmission terminates.

Each node generates a random backoff timer chosen uniformly from the range [0, w-1], where w is referred to as the contention window. At the first transmission attempt, w is set to w_{min} (minimum contention window). After the backoff timer reaches 0, the node transmits a short RTS message. If the RTS is successfully received, the receiving node responds with a CTS message. Any other node which hears either the RTS or CTS message uses the data packet length information to update its Network Allocation Vector (NAV) containing the information of the period for which the channel will remain busy. Thus, all nodes including hidden node can defer transmission appropriately to avoid the packet collision.

An acknowledgement (ACK) packet will be sent by the receiver upon successful reception of a data packet. It is only after receiving an ACK packet correctly that the transmitter assumes successful delivery of the corresponding data packet. If there is no response of ACK or CTS packet, a binary exponential backoff scheme is used. After each unsuccessful transmission, the value of w is doubled, up to the maximum value w_{max}.

Short InterFrame Space (SIFS), which is smaller than DIFS, is a time interval between RTS, CTS, data packet, and ACK. Using this small gap between transmissions within the packet exchange sequence prevents other nodes from attempting to use the medium. As a consequence, it gives priority to completion of the ongoing packet exchange sequence.

2.2 Multi-rate in IEEE 802.11

Multi-rate in IEEE 802.11 provides physical-layer mechanism to transmit at higher data rates than the basic rate if the channel conditions permit. The first commercial implementation that exploits this multi-rate capability is called Auto Rate Fallback (ARF) [12]. With ARF, transmitters use the history of previous transmission error rates to adaptively select the next transmission rate. That is, after a number of consecutive successful transmissions, the transmitter changes its modulation scheme to attempt the transmission at a higher rate, and vice versa after consecutive losses. Consequently, if a mobile user has a perpetually high-quality channel, the user will eventually transmit at higher data rates while accessing the medium according to the same IEEE 802.11 MAC.

An enhanced protocol to exploit the multi-rate capability of IEEE 802.11 named Receiver Based Auto Rate (RBAR) is proposed in [13]. The key idea of RBAR is for receivers to control the transmitter's transmission rate. RBAR uses physical-layer analysis of the received RTS message to determine the maximum possible transmission rate for a particular bit error rate. The receiver inserts this rate into a special field of the CTS message to inform the transmitter and other overhearing nodes of the potentially modified rate. This message is called reservation-sub-header (RSH) and is inserted in the header of the data packet. With the RSH message, overhearing nodes can modify their NAV values to the new potentially decreased transmission time. In this way, RBAR quickly adapts to channel variations and extracts significant throughput gains as compared to ARF.

Any one of the previous multi-rate methods can be merged into the proposed method as will be explained in the next section. However, our design goal is that the deployed nodes need not to be modified. Thus, we propose that the transmitter estimates the wireless channel quality by using the SNR of the received CTS message.

3 Opportunistic Packet Scheduling

3.1 Channel Access Method

For the uplink channel, each node transmits data packets by using the DCF mechanism. For the downlink channel, we propose a collision-free channel access

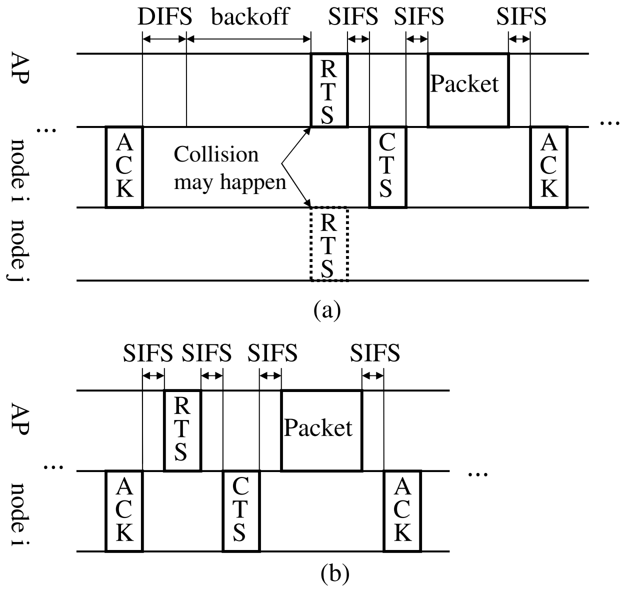

Fig. 1. Downlink channel access method (a) DCF and (b) CFCA

(CFCA) mechanism in addition to the DCF mechanism. That is, AP can select different channel access mechanism between two, DCF and CFCA, for each data packet transmission.

The DCF mechanism is illustrated in Fig. 1(a), where the next channel access should wait for DIFS and backoff window time after the previous ACK packet. A two-way handshaking technique without RTS/CTS handshaking called basic access mechanism is not considered in this paper although our proposed method can be easily extended to the basic access mechanism. The CFCA mechanism is illustraed in Fig. 1(b). In this method, the AP waits only for SIFS time instead of DIFS and backoff time. By shortening the waiting time, the AP can access the channel without collision because all other nodes should wait at least DIFS time which is longer than SIFS time. The more the AP selects the CFCA as the channel access method, the more throughput is allocated to the downlink because neither packet collision nor backoff occurs during the CFCA.

To limit the throughput superiority of the downlink channel caused by the CFCA, the selection algorithm between the two channel access mechanisms is required. That is, the frequency of the CFCA should be limited. We propose that the AP determines the channel access method depending on the history of the previous successful data packet transmissions to adaptively select the next channel access method. Let γ denote the required throughput ratio between the uplink and the downlink. For the implementation of the proposed method, AP keeps track of the successful packet transmissions. If the downlink transmits more data packets than γ, AP selects the DCF to give more throughput to the uplink. If the downlink transmits less data packets than γ, AP selects the CFCA to get more chance of packet transmission through the downlink. The value of γ can be set to any values and we set it to one except otherwise specified.

3.2 Packet Queue Management and Scheduling in AP

Each node can directly communicate only with the AP (uplink or downlink), since we focus on the AP-coordinated wireless network. The AP manages the downlink packet queues for each node as shown in Fig. 2. During the DCF, the packet scheduling algorithm adopts the first-in first-out (FIFO) algorithm. During the CFCA, the AP schedules the packet based on the channel quality. The link with better channel quality is given higher priority in packet transmission. In order to track the latest channel quality, it is necessary to send the control packet to the node. However, this method will increase the overhead and need the modification of the IEEE 802.11 standard. Our design goal is that the scheduling method can be implemented without the modification of the nodes already deployed in the system. Thus, we propose that the AP updates the channel quality of each link after every successful packet transmissions. The channel quality is reported from the physical layer by measuring the SNR of the CTS and ACK control packets as explained in the previous section. This estimation of the channel quality may not be the timely information. However, the estimation error is in the acceptable range as will be shown in the next section. Moreover, the proposed method can be implemented without the modification of the deployed nodes.

The AP lists all the communication links according to the channel quality. When the AP selects the CFCA mechanism for the channel access method, the link that recorded the best channel quality in the previous successful packet transmission is given the first chance to transmit the packet in the queue. When there is no packet in the queue for that link, the next good-quality link is given the second chance to transmit the packet.

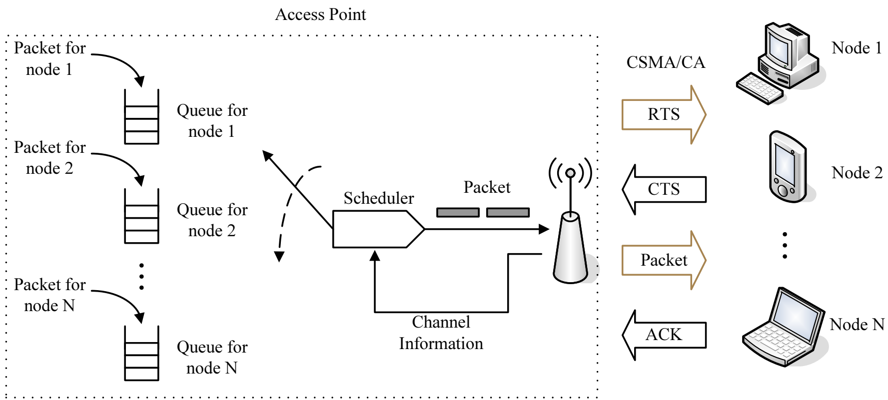

Fig. 2. Queue management in AP

Most functions of the IEEE 802.11 have been integrated in a single integrated circuit (IC) [14]. The operations of the channel access and the packet scheduling are performed by the IC. The proposed method can be implemented with a small increase of logic gates such as counters and comparators in the IC. Thus, the implementation of the proposed method does not require additional delay or computing power. The modification of the IC is required only for the AP and is not required for the nodes.

4 Numerical Results

We evaluate the performance of the proposed method, named opportunistic packet scheduling (OPS), by computer simulations. The IEEE 802.11 DCF is compared with the OPS. The parameter values used to obtain the numerical results of the simulation runs are summarized in Table 1. The values of these parameters are based on the IEEE 802.11b direct sequence spread spectrum (DSSS) standard [1].

Table 1. Parameter values

Parameter	Value
w_{min}	32
w_{max}	1024
SIFS time	10 μs
PIFS time	30 μs
DIFS time	50 μs
slot time	20 μs
MAC header	272 bits
PHY header	48 bits
Preamble	144 μs
ACK time	304 μs
RTS time	352 μs
CTS time	304 μs

To reflect the fact that the surrounding environmental clutter may be significantly different for each pair of communication nodes with the same distance separation, we use the log-normal shadowing channel model [15]. The path loss PL in dB at distance d is given as

$$PL(d) = PL(d_0) + 10n \log(d/d_0) + X_\sigma, \quad (1)$$

where d_0 is the close-in reference distance, n is the path loss exponent, and X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. We set n to 3.25 and σ to 5.2 according to the result of measurements for an office building model [15]. To estimate $PL(d_0)$, we use the Friis free space equation

$$P_r(d_0) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L}, \quad (2)$$

where P_t and P_r are the transmit and receive power, G_t and G_r are the antenna gains of the transmitter and receiver, λ is the carrier wavelength, and L is the system loss factor which is set to 1 in our simulation. Most of the simulation parameters are drawn from the data sheet of Cisco 350 client adapter. The received power is

$$P_r(d) = P_t - PL(d). \tag{3}$$

The minimum received power level for the carrier sensing is set to -95 dBm, which is the noise power level. The long-term SNR is

$$SNR_L = P_t - PL(d) - n + PG, \tag{4}$$

where n is the noise power set to -95 dBm and PG is the spread spectrum processing gain given by

$$PG = 10 \log_{10} \frac{C}{S}, \tag{5}$$

where C is the chip rate and S is the symbol rate. Since each symbol is chipped with an 11-chip pseudonoise code sequence in the IEEE 802.11 standard, PG is 10.4 dB. The received SNR is varied by the Ricean fading gain δ. Under this model, the SNR of the received signal is

$$SNR = 20 \log_{10} \delta + SNR_L. \tag{6}$$

For the data rate in the physical layer for each communication link, we assume that the system adapts the data rate by properly choosing one from a set of modulation scheme according to the channel condition. The set of modulation schemes used in our simulation studies are BPSK, QPSK, 16QAM, 64QAM, and 256QAM. For the simplicity, we ignore other common physical layer components such as error correction coding.

We assume that all nodes except the AP are randomly distributed in the circle area with a diameter of 150 meters and move randomly at a speed of 0.1 m/sec. The AP is located at the center of the area. To evaluate the maximum performance, traffic load is saturated and the destination addresses of the packets are the AP in each node. In the AP, there are N connections, each for one node, and packets are generated for each connection with the same distribution as those in each nodes. To make an asymmetric traffic load condition between the uplink and the downlink, the size of the downlink and the uplink packets are 1024 and 64 bytes, respectively. The number of node is set to 25. The effects of the number of nodes on the performance is evaluated by the computer simulation.

The system throughput of the proposed method is compared with the DCF in Fig. 3. In the DCF, the system throughput decreases as the number of nodes increases. This decrease of the system throughput mainly comes from the increased collision between the packet transmissions. It is noted that the probability of the packet collision increases as the number of nodes increases. On the contrary, the

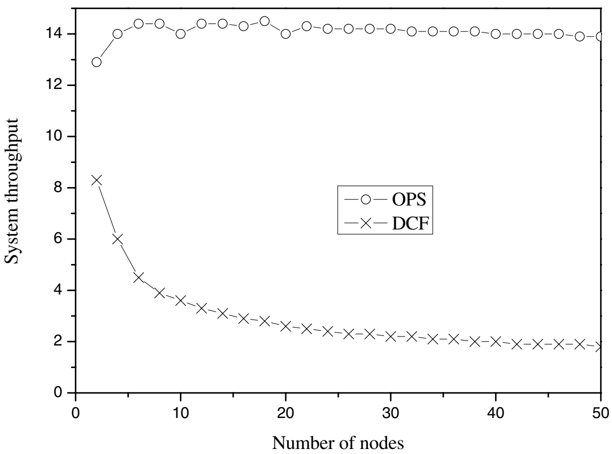

Fig. 3. System throughput versus the number of nodes

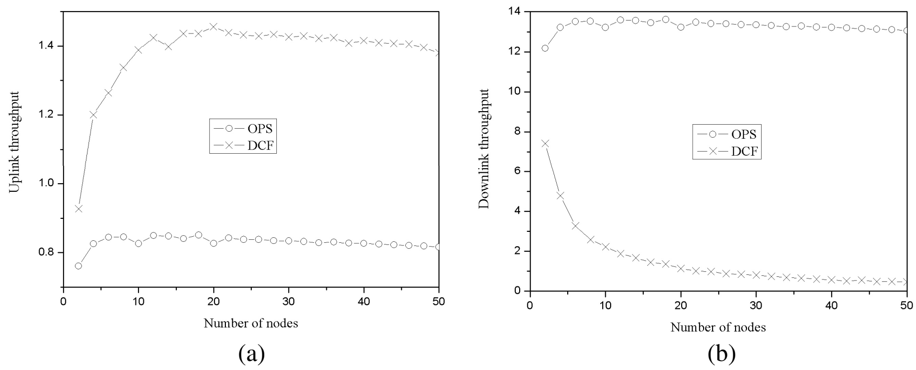

Fig. 4. (a) Uplink and (b) downlink throughput versus the number of nodes

OPS maintains a constant system throughput because it provides contention-free channel access method for the AP. Moreover, the OPS enjoys more system throughput because higher data rate is provided for the packet transmission during the CFCA.

The uplink throughput is shown in Fig. 4(a). The uplink throughput of the DCF increases as the the number of nodes increases. For a large number of nodes, the uplink throughput is saturated because of the increased number of collisions and backoff mechanism. The OPS provides constant throughput to the uplink compared with the DCF because the throughput is controlled by the selection algorithm of the two channel access methods. The downlink throughput is shown in Fig. 4(b). The decrease of the downlink throughput is proportional to the number of nodes in the DCF. Note that system throughput decreases as the number of nodes increases, which is explained in Fig. 3. It is shown that the OPS provides larger throughput to the downlink and can mitigate the bottleneck problem in the asymmetric traffic load condition. The throughput of the OPS is constant because of the same reason as in Fig. 4(a). Because we assign asymmetric traffic load between the uplink and the downlink, the downlink is allocated more throughput than the uplink in the simulation.

5 Conclusion

We have proposed an opportunistic packet scheduling method to alleviate the throughput unbalance between the uplink and the downlink and to enhance the system throughput of the IEEE 802.11 DCF. The proposed method also reduces the probability of the data packet collision. The proposed method can be implemented without the modification of the IEEE 802.11 standard for nodes that are widely deployed.

The efficiency of the proposed system has been demonstrated by the computer simulation. The results show that the proposed method enhances the system throughput for asymmetric traffic load. This, in turn, drastically reduces the blocking probability of the multimedia data packets in the proposed systems compared with that in the IEEE 802.11 DCF.

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