A Rate Separation Mechanism for Performance Improvements of Multi-rate WLANs

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Abstract. The fundamental access mode of the IEEE 802.11 MAC protocol is contention based. If the traffic load is heavy or the number of contending station is large, the number of collisions is increased and it leads to the performance degradation. In this paper, we propose a mechanism that tries to reduce the number of collisions by separating and grouping the contending stations and distributing those groups over time in multi-rate WLANs. For this, we issue the trade-off relationship between the throughput fairness and temporal fairness in multi-rate WLANs. Considering the trade-off relationship, we propose a Rate Separation (RS) mechanism in which the grouping is done based on the current transmission rates of contending stations. From our simulation study, we show that the proposed mechanism reduces the number of collisions and achieves improved performance over the IEEE 802.11b WLANs.

1 Introduction

The IEEE 802.11 standard defines the physical (PHY) and Medium Access Control (MAC) layers for both infra-structured and ad hoc networks [4]. The original standard supports the data rates of 1 and 2 Mbps. To provide higher bandwidth to users, the IEEE 802.11b standard [8] has been published. In this standard, a high-rate PHY extension for the direct sequence spread spectrum (DSSS) system is specified in the 2.4 GHz band and it provides additional 5.5 and 11 Mbps data rates. The IEEE 802.11a PHY extension [10] is a new standard that operates at the 5 GHz band with Orthogonal Frequency Division Multiplexing (OFDM) radio and provides the data rate ranging from 6 Mbps up to 54 Mbps.

All of the IEEE 802.11 extensions use the identical MAC protocol. The IEEE 802.11 MAC provides two channel access mechanisms, namely, Distributed Coordination Function (DCF) and Point Coordination Function (PCF). DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access mechanism while PCF is based on a simple polling mechanism. The contention based DCF is the mandatory access mode of IEEE 802.11 while PCF is an optional function for contention-free access mode. In this paper, only the basic access mode (DCF) is considered for discussion.

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In the DCF mode, when there are many stations or massive load in a BSS (Basic Service Set), collisions occur frequently and much of the bandwidth is wasted. The probability of collisions is directly proportional to the number of contending stations and the collisions give significant negative impacts on the overall performance. [5,6,7] discussed this impact on the performance of IEEE 802.11 via numerical analysis and simulations. To tackle this problem, the authors in [6,7] proposed adaptive backoff algorithm which adaptively controls the contention window size based on the traffic condition of the network to reduce the collisions. But, these works limited by assuming the wireless network of a single transmission rate. In multi-rate WLANs, there is another problem affecting the network throughput due to the fact that the transmissions of stations at low rates take more time than those of stations at high rates [1,2,3]. In multi-rate WLANs, it seems to reasonable that the stations at high rates should transmit more data packets than those at low rates to enhance the network throughput. But, as the IEEE 802.11 MAC gives the equal number of channel accesses to each station regardless of its transmission rate, the network throughput is degraded when there are many stations at low rates. To enhance the network throughput in this case, a new scheme considering the transmission rate of stations is required.

In this paper, we propose a simple mechanism that tries to reduce the probability of collisions by grouping the contending stations and distributing them into several time periods. For the grouping of stations, we introduce a transmission rate based grouping strategy considering the characteristic of multi-rate capability of IEEE 802.11b. In this mechanism, only stations permitted by an AP (Access Point) can contend for the medium during a given time period. By doing this, the number of contending stations are dramatically decreased, and thus, the number of collisions is also reduced. This eventually leads to the improved performance. To provide fairness among the stations in terms of throughput and temporal share, the time periods are adaptively adjusted by the AP according to the network condition.

2 IEEE 802.11 DCF

The mandatory DCF, which is based on CSMA/CA, is the primary access protocol for the automatic sharing of the wireless medium between stations and APs having compatible PHYs. As described in [4], before a station starts transmission, it must sense whether the wireless medium is idle for a time period of Distributed InterFrame Spacing (DIFS). If the channel appears to be idle for a DIFS, the station generates a random backoff time, and waits until the backoff time reaches 0. The reason for this is to reduce the collisions occurred by the situation that many stations waiting for the medium to become idle can transmit frames at the same time. Thus, the distinct random backoff deferrals of stations can reduce the collision probability.

The DCF mode provides two different handshaking protocols for frame transmissions. In DCF, a sending station must wait for an ACK frame from the receiving station. This is due to the fact that the sending station cannot correctly detect a collision at the receiving station, and it cannot listen to the medium while it is transmitting due to the difference between the transmitted and the received signal power strengthes for the wireless medium. Thus, the basic handshaking procedure of DCF for data frame exchanges follows a DATA-ACK sequence. An optional handshaking procedure requires that the sending station and the receiving station exchange short RTS (Request-To-Send) and CTS (Clear-To-Send) control frames prior to the basic handshaking procedure. The RTS/CTS exchange provides a virtual carrier sensing mechanism in addition to physical carrier sensing to prevent the hidden terminal problem. Any stations hearing either a RTS or CTS frame update their Network Allocation Vector (NAV) from the duration field in the RTS or CTS frame. All stations that hear the RTS or CTS frame defer their transmissions by the amount of NAV time. The overhead of RTS/CTS frames exchange becomes considerable when data frame sizes are small. Thus, RTS/CTS frame exchange should be based on the size of a data frame. IEEE 802.11 defines a configurable system parameter, *dot11RTSThreshold*, for RTS/CTS exchange.

3 Proposed Mechanism

3.1 Traffic Separation by Transmission Rate

In this section, we present a mechanism termed Rate Separation (RS). We assume a network topology of a single cell (BSS: Basic Service Set) controlled by an AP (Access Point) where all traffics occur between the AP and stations. In the RS mechanism, the AP can group the stations based on their transmission rates and allocate proper resources to each group. Figure 1 illustrates the basic idea of the RS mechanism. As shown in the figure, a periodic super-frame consists of multiple sub-frames. Each sub-frame is started by the Separation Beacon Messages (SBMs). Figure 2 shows the structure of the SBM. In the figure, the 1-bit *SBM* flag is used to indicate that this beacon is SBM and the 16-bit *Duration* field is the duration of the current contention block (sub-frame period) initiated by the SBM. The 7-bit *Rate* field is used to indicate the transmittable rate(or multiple rates) in the sub-frame period. The transmittable rate means that only the stations at the same transmission rate specified in the SBM can join the contentions to get the medium. By the *Rate* field in the SBM, the contentions for the medium of each station is separated by its current transmission rate. For

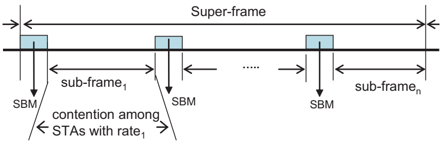


Fig. 1. Rate Separation Mechanism

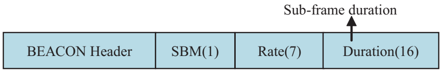


Fig. 2. Separation Beacon Message Format

example, assuming there are 11Mpbs, 5.5Mbps and 2Mbps transmission rates, the first SBM can be used to announce that only the stations at 11Mbps have a chance for transmission, and the second and third SBMs are used for stations at 5.5Mbps and 2Mbps, respectively.

In the RS mechanism, to calculate the proper duration of each sub-frame the AP should maintain a network information table which includes station's ID, the current transmission rate, and the average packet size. The AP can know easily which stations are in its BSS through the association procedure between the AP and stations, and the current transmission rate of each station by measuring SNR (Signal-to-Noise Ratio). Since the transmission times for a data payload of the same length can be different according to transmission rates, the AP should know the average transmission time for each transmission rate group to calculate the value of the *Duration* field in the SBM. Based on the network information table, the AP calculates the duration of each sub-frame and super-frame, and allocates the resource for stations. The duration D_{Super_frame} and $D_{Sub\_frame_i}$ can be determined by the following equations.

Suppose that D_{Super_frame} and D_{Sub_frame} are the duration of the super-frame and the sub-frame, respectively, and let N_{Rate_i} be the number of stations at $Rate_i$ and T_{Rate_i} be the average transmission time of stations at $Rate_i$. Then, D_{Super_frame} and D_{Sub_frame} can be determined by the following equations.

$$D_{Super\_frame} = \sum_{Rate_i} D_{Sub\_frame_i} \tag{1}$$

$$D_{Sub\_frame_i} = N_{Rate_i} \cdot T_{Rate_i} \cdot \alpha \tag{2}$$

where α is the fraction factor which determines the duration of each sub-frame. If α value is larger than 1, statistically, all stations in a group have a chance to transmit a data frame at least once. Excessively or insufficiently allocated sub-frame duration may degrade the network performance. When the sub-frame duration is allocated excessively ($\alpha >> 1$), the fairness problem can arise or the network utilization can be worsen due to the idle time wasted in the sub-frame if there are not enough stations. Contrarily, when the allocated sub-frame duration is insufficient ($\alpha << 1$), the number of collisions can increase and some stations can't transmit their frames and should wait until the next sub-frame. By Equations (1) and (2), stations in each group have different chances of getting the channel according to their transmission rates.

The key idea of the RS mechanism is to reduce the number of contending stations by separating them according to their transmission rates and distributing those groups over time. Suppose that the number of contending stations is n. In the IEEE 802.11 MAC, when the current transmission is finished, all n stations participate in the contention for the medium. As discussed in [6,7], the probability of collisions is directly proportional to the number of contending stations and the collisions give significant negative impacts on the overall performance. But, in the RS mechanism the contending stations are grouped and separated by their current transmission rates and the number of contending stations is limited for a given period. Thus, when the current transmission is finished, not all n stations but some among n stations participate in the contention for the medium. Since the other stations that do not currently participate in the contention have a chance to contend for the medium in the next period, the RS mechanism tries to reduce the probability of collisions by grouping the contending stations and distributing them into several time periods which can be dynamically adjusted by the AP according to the network condition. There can be different criteria for grouping the stations, but we choose the station's current transmission rate as a grouping criterion because it is one of the primary factors that directly affect the network performance [2,3].

3.2 Adaptive Sub-frame Allocation

In the RS mechanism, an improper channel allocation by the AP can arise due to several facts: (1) station's coming in and out of a BSS, (2) changes of stations' transmission rates due to mobility within a BSS, and (3) burst traffic generation at stations. (1) and (2) can be easily treated by the AP via the reassociation procedure and continually monitoring the transmission rate of each station. Thus, those changes can be easily updated to the network information table and the updated information can be announced in the next SBM frame. But, it is very difficult to solve (3). For this, we propose a delay sensing mechanism that the AP sends the next SBM frame immediately, after it detects that there is no traffic for a certain period of time. The following Equation (3) shows the timeout value for the delay sensing denoted by $T_{ds\_timeout}$.

$$T_{ds\_timeout} = T_{DIFS} + T_{delay\_sense} \tag{3}$$

where $T_{delay\_sense} = T_{slot} \cdot W_{delay}$ is the acceptable time to continue the sub-frame even if there is no traffic and W_{delay} is the window size for the delay sensing.

When there are few stations in the BSS, the RS mechanism may not be efficient since the probability of collisions is low and there are enough temporal resources for stations. Moreover, the frequent generation of SBM frames can be overhead, and may disturb the transmission of other stations. Thus, we adaptively use the RS mechanism. If the duration of a sub-frame is below a certain threshold value, the sub-frame is merged with the next sub-frame. As a result, if the number of sub-frames is more than two in a super-frame, the RS Mechanism is turned on. Figure 3 shows the algorithmic description of the adaptive RS mechanism.

3.3 Rate Fairness

In single transmission rate WLANs, the throughput fairness implies the fair channel occupancy time among stations. As the equal number of channel accesses is guaranteed by the random contention mechanism of CSMA/CA, each

```
for(all rates)
    if(duration of sub-frame < threshold)
        merge with the next sub-frame
    else
        allocate the sub-frame
if (number of sub-frames >= 2 )
        ON the rate separation mechanism
else
        OFF the rate separation mechanism
```

Fig. 3. Adaptive RS Algorithm

station can have the equal amount of time share and thus can achieve the equal throughput in single rate WLANs. But, in multiple rates IEEE 802.11b or IEEE 802.11a, they do not have the same meaning any more. If providing the throughput fairness is a primary concern, as the legacy 802.11 MAC provides, the wireless channel becomes under-utilized because a large portion of the channel (time) is occupied by the long low rate transmissions. Considering that the transmission time for 1 packet at 2Mbps gives the time for 5 packets transmissions at 11Mbps, we can easily expect that giving the same transmission opportunity to the stations regardless of their transmission rate will lead to overall network throughput reduction. On the other hand, if providing fair temporal share (temporal fairness) is the primary concern, stations at high rates should be given more chances to transmit to make up their relatively shorter transmission time compared to the long low rate transmission. In this case, achieving the temporal fairness (by some means) gives improved throughput performance, but the throughput fairness among the stations is broken.

To provide the fair share of the medium resource, we make use of the fact that the AP controls everything related to the medium resource in the RS mechanism. The AP can dynamically control the sharing of the channel by considering both the throughput fairness and the fair temporal share. This can be achieved by modifying the Equation (2) as follows.

$$D_{Sub\_frame_i} = \alpha \cdot \left(N_{Rate_i} \cdot T_{Rate_i} \cdot \beta + N_{Rate_i} \cdot T_{Rate_{highest}} \cdot (1 - \beta) \right) \quad (4)$$

where $T_{Rate_{highest}}$ is the average transmission time of stations at the highest rate in the system, and β is the fairness preference factor and it has a value between 0 and 1. $N_{Rate_i} \cdot T_{Rate_i} \cdot \beta$ in Equation (4) is related to the throughput fairness because all stations in each transmission rate group have statistically have a chance to transmit a data frame. $N_{Rate_i} \cdot T_{Rate_{highest}} \cdot (1 - \beta)$ is related to the temporal fairness because the transmission time is adjusted to that of the highest rate. For example, if β =0, then the AP allocates the medium based on the throughput fairness while the resource is allocated by the temporal fairness basis when β =1. In the next section, we investigate the impact of β on the performance.

4 Performance Evaluation

In this section, we present the results of our simulation study using the *NS2* simulator [9]. Figure 4 shows the network topology used in our simulation study.

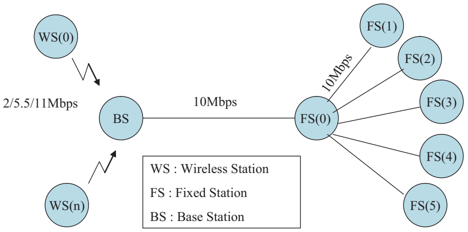
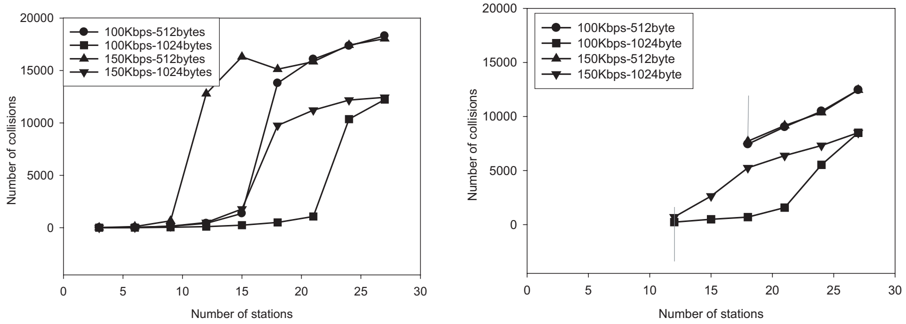


Fig. 4. Network Topology for Simulation

As shown in the figure, there are n wireless stations (*WS(0) - WS(n)*) in the wireless part and six fixed stations *(FS(0) - FS(5))* exist in the wired part. We assume that the wireless stations support data rates of 2, 5.5, and 11Mbps and use the DCF mode with the RTS/CTS handshake. Each *WS* is a CBR (Constant Bit Rate) traffic source to a *FS*. Each *FS* in the wired part can have maximally 6 traffic sinks at a time. Each *WS* generates the CBR traffic at the rate of 100Kbps or 150Kbps. For a given traffic load, we also vary the packet size to 512 and 1024 bytes. At the same traffic load, the 512 byte packet sending rate is twice faster than the 1024 byte packet sending rate. So, when the smaller packet size (512 byte)is used, there are more chances of collisions. Throughout the whole simulation runs, the number of stations at each transmission rate is equally divided. The RS mechanism starts activating when the number of stations is above 18 when the packet size is 512 byte and 12 when it is 1024 byte. The fraction factor α in Equation (4) is set to 1 and the rate fairness preference factor β values in Equation (4) is varied to 0, 0.5 and 1 to measure its impact on the performance.

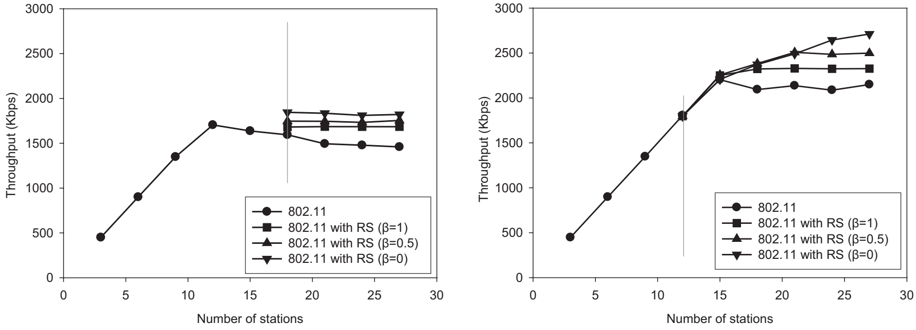
Figure 5 shows the number of collisions observed during the whole simulation time as a function of the number of contending stations. Figure 5(a) shows the case when the IEEE 802.11 MAC is used. In the figure, we can see that the number of collisions rapidly increases as the number of contending stations are increased. By comparing the plot of 100Kbps-512bytes and 100Kbps-1024bytes, we can also verify that the number of collisions is more rapidly increased when the packet sending rate is higher. Figure 5(b) shows the number of collisions when the RS mechanism is used. Compared to Figure 5(a), the number of collisions is significantly reduced due to the fact that the RS mechanism tries to group the contending stations based on their transmission rates and temporally distribute them into several sub-frame durations. Note that we do not show the number of collisions in Figure 5(b) when the number of contending stations is less than the threshold at which the RS mechanism is activated (18 and 12 stations for



(a) IEEE 802.11

(b) RS mechanism

Fig. 5. Number of collisions



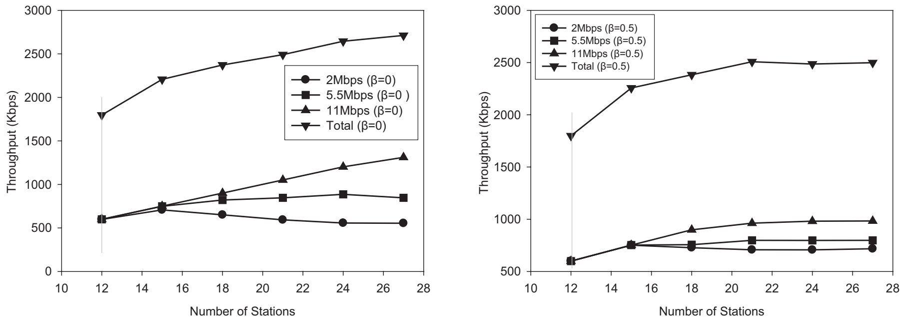
(a) 150Kbps, 512byte

(b) 150Kbps, 1024byte

Fig. 6. Network throughput

512 and 1024 byte packets respectively), because the number of collisions is the same as the one in Figure 5(a) until the number contending stations reaches the thresholds. In the figure, we can see that the plots of the number of collisions are divided into two groups according to the packet size regardless of the packet sending rates: (100Kbps-512bytes, 150Kbps-512bytes) and (100Kbps-1024bytes, 150Kbps-1024bytes) groups.

Figure 6 compares the overall network throughput performance by varying β. Only the cases of 150Kbps-512bytes (Figure 6(a)) and 150Kbps-1024bytes (Figure 6(b)) are shown because other cases shows very similar behavior. As shown in the figure, the network throughput is improved regardless of the value of β when the RS mechanism is used. In the case of the IEEE 802.11 MAC, we can see that the network throughput is saturated, or even has a tendency to decrease, when the number of contending stations increases. When the RS mechanism is used, we can see that the highest network throughput is achieved when $\beta = 0$. As discussed, this is mainly due to fact that the temporal fairness is maximally achieved by giving more transmission opportunities to the stations



(a) 150Kbps, 512byte (b) 150Kbps, 1024byte

Fig. 7. Group throughput

at high rates. When $\beta = 1$, we can see that the amount of throughput improvement is the smallest because equal transmission chances are given to all stations regardless of transmission rate. Figure 7 shows the aggregated throughput of each transmission rate group when β is 0 and 0.5, as a function of the number of contending stations. As shown in the figure, the throughput difference among the different transmission rate groups become smaller, i.e. the throughput fairness is improved as β is increased to 0.5. Note that this achieves at the cost of the total network throughput reduction which can be verified in the figure.

Figure 8 shows the throughput performance of the RS mechanism when the number of WS is fixed to 27 and β values varied to 0, 0.5, and 1. Both the network throughput and the group throughput are shown varying the traffic loads. As discussed, we can see from the figure that there is a trade-off between the network throughput and temporal fairness. One possible solution for resolving this trade-off is to compromise between the temporal fairness and the throughput fairness with the same preference factor ($\beta = 0.5$). In this case, we can achieve moderate network throughput improvement and temporal fairness. As the switching between emphasizing the network throughput and emphasiz-

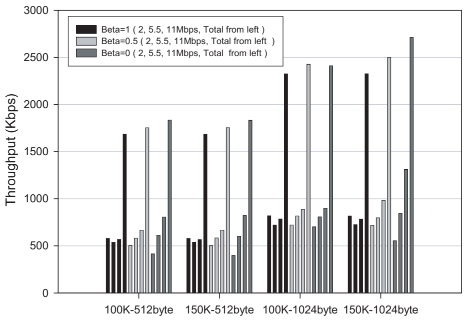


Fig. 8. Rate fairness, Number of Station = 27

ing the temporal fairness can be done easily by simply changing the sub-frame duration, the AP can dynamically control the network resource at any time it wants.

5 Conclusions

The performance of the IEEE 802.11 DCF is strongly dependent on the number of contending stations. In this paper, we issued the trade-off relationship between the throughput fairness and temporal fairness in multi-rate WLANs. We proposed a mechanism that tries to reduce the number of collisions by separating and grouping the contending stations, and distributing those groups over time. Considering the trade-off relationship above in multi-rate WLANs, as one of the grouping strategies, we proposed the Rate Separation (RS) mechanism in which the grouping is done based on the current transmission rates of contending stations. From the simulation study, we verify that the proposed RS mechanism reduces the number of collisions and achieves the improved performance.

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