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A Dynamic and Adaptive Transmission Scheme for Both Solving Uplink/Downlink Unfairness and Performance Anomaly Problems in a Multi-Rate WLAN

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Abstract: Uplink/downlink fairness and performance efficiency are both considerable issues in an IEEE 802.11 multi-rate Wireless Local Area Network (WLAN). The IEEE 802.11 Distributed Coordination Function (DCF) provides equal medium access probability to all transmitters that cause the access point (AP) to obtain less bandwidth than that of the wireless mobile stations to download traffic when the number of mobile stations is larger than one. Furthermore, the WLAN with infrastructure mode also has the performance anomaly problem that the system throughput was seriously degraded by the transmissions of lower date rate transmitters in a multi-rate environment. In the past studies, many mechanisms have been proposed to solve the uplink/downlink unfairness problem, such as the transmission opportunity mechanism (TXOP), the multiple backoff timer mechanism (MBT) and the asymmetric access point mechanism (AAP). In order to improve the performance efficiency, contention window differentiation mechanism (CWD), packet size differentiation mechanism (PSD) and interframe gap differentiation mechanism (IFG) have been proposed recently. The proposed mechanisms, however, did not take both uplink/downlink unfairness and performance anomaly problems into consideration at the same time. In fact, the two problems occur simultaneously in practical WLAN environments. In this paper, we propose a dynamic and adaptive transmission scheme (DAT) to deal with the both problems. Each wireless mobile station will consider its data rate to decide the number of packets to transmit when it gets the privilege to access medium. Moreover, the AP has more right to download more packets for the purpose of balancing total uplink traffic. The system throughput of the proposed DAT is discussed and validated by the simulations and analytical results. The simulations also show that the proposed DAT outperforms the previous mechanisms.

Keywords: IEEE 802.11, uplink/downlink unfairness, performance anomaly, TXOP, MBT, AAP, CWD, PSD, IGP.

1 Introduction

Wireless local area networks (WLANs) based on the IEEE 802.11 standard [1] have been very popular and widely deployed in public and private areas for web-browsing, downloading files, e-mails, peer to peer applications, voice over IP (voip) and so on. Most IEEE 802.11 WLANs are deployed in the infrastructure mode and adopted multiple transmission rates to adapt to different communication situations. The IEEE 802.11 distributed coordination function (DCF) provides equal channel access probability to all devices in the WLAN, including the access point (AP) and mobile stations. When the WLAN is configured in the infrastructure mode, the mobile station has to contend with other mobile stations to transmit its frames to the AP first and then AP will forward the packets to its corresponding destination. Besides, the AP has to be responsible for dispatch packets from the wired networks. Therefore, the current DCF design makes the AP become the bottleneck and results in significant Uplink/Downlink unfair sharing problem. From theoretical analysis, when N mobile stations and one and only one AP try to access the channel, the AP approximately acquires 1/(N+1) channel access probability to download frames. While all mobile stations could gain N/(N+1) chance to upload frames. The legacy solutions to this unfairness problem can be simply classified into time domain and frequency domain methods. The time domain methods, such as [2][3], provide the AP with a greater transmission opportunity, namely the transmission opportunity mechanism (TXOP), to send more data frames when the AP gets the right to access the channel. The frequency domain methods, including the multiple backoff timer mechanism (MBT) [4] and the asymmetric access point mechanism (AAP) [5], give the AP higher transmission probability to send more times than the mobile stations to improve the throughput of the downlink traffic. The MBT is to have the AP employ multiple independent backoff timers, each of which is associated with each downlink traffic flow. The AAP is to give the AP transmission capacity that is k times greater than the capacity of all the mobile stations. This means that the AP can obtain kN times greater channel access probability compared to one mobile station, where N is the number of active mobile stations in the WLAN and k represents the number of data segments per TCP ACK.

On the other hand, IEEE 802.11 provides a high level of support for multi-rate transmission environments. For example, IEEE 802.11b supports rates of 1, 2, 5.5 and 11 Mbps respectively, while IEEE 802.11a supports eight different transmission rates ranging from 6 to 54 Mbps. However, the IEEE 802.11 standard faces a fundamental performance anomaly problem [6] in multi-rate environments. This problem mainly occurs in two situations. The first is that when the slower node gets the right to access the channel, it will take longer time to send out the same size of packet than the time higher rate node will spend. The second is that when the slower nodes get collided with the higher rate ones, the collision period has to wait the slower nodes to finish their transmission so that it takes more time than the time which the collided nodes with the same higher rate consume. At present, three basic methods exits for enhancing the performance of IEEE 802.11 medium access control (MAC) by assigning different channel priorities to stations with different rates, namely packet size differentiation (PSD) [7], contention window differentiation (CWD) [8,9] and interframe gap differentiation (IFP) [10]. In the PSD approach, the size of the packets transmitted by the different stations is varied in accordance with their respective data rates, that is, high-rate stations transmitted longer packets, while low-rate stations transmit shorter packets. Although the PSD method yields a notable improvement in the network performance, it requires the packets to be fragmented at the sender and then reassembled at the receiver, which not only increases the computational burden at the MAC layer, but also consumes a greater amount of power. In the CWD method, the high-rate stations are simply assigned a smaller contention window (CW) such they can access the channel more easily. Finally, in the IFG approach, high-rate stations with a shorter IFG are granted preferential access to the channel relative to those low-rate stations with a longer IFG. However, while the IFG method improves the network performance, it inevitably induces a temporal unfairness among the various channel users.

In this paper, we consider the uplink/downlink unfairness and performance anomaly problems together and proposed a dynamic and adaptive transmission scheme (DAT) for solving both problems in a multi-rate WLAN.

The remainder of the paper is organized as follows. The DAT scheme is proposed in Section 2 and the analytical throughput model for the proposed DAT is discussed and validated in Section 3. Section 4 describes the simulation results. Section 5 presents the conclusion and indicates the future research.

2 The Proposed Scheme

By the study of the related work, we found that previously individual solutions to both problems by tuning the same parameters, i.e. CW, TXOP or IFS, to accomplish their goals. Also, we don't plan to modify the basic operations of IEEE 802.11 behaviors and reserve the temporal fairness property for each wireless mobile station. It means that the transmitter with higher data rate will transmit more packets once it gets the right to access the channel and the slower one will transmit fewer packets for mitigating the performance anomaly problem, but each mobile station occupies almost the same channel access time. Moreover, the AP is designed to transmit packets that are equal to summation of traffic each mobile station can send one time to solve the asymmetric uplink/downlink bandwidth sharing problem.

More specifically, assume that there are one AP with the fixed data rate and N wireless stations with m varied data rates in a multi-rate WLAN, where the date rate ranging from low to high is R_1 to R_m, i.e. $R_1 < R_2 < \cdots < R_m$, and the data rate of AP is fixed at R_m. The number of nodes with data rate R_i is n_i and the number of total nodes in the system is $N\ (= n_1 + n_2 + n_3 + \cdots + n_m)$. When the wireless station with data rate R_j gets the privilege to access the medium, it can transmit $Q_j = \left\lceil \frac{R_j}{R_1} \right\rceil$ packets and the AP can transmit $Q_{AP} = [n_1 + \frac{R_2}{R_1} \times n_2 + \frac{R_3}{R_1} \times n_3 + \cdots + \frac{R_m}{R_1} \times (n_m - 1)]$ packets.

3 Throughput Analysis And Model Validation

The derived system saturation throughput for the proposed DAT is referred to the previous study [11]. The important notations and symbols used are shown in Table I.

Table I. Notations used in the throughput analysis

Notations	Meaning and explanation
σ	The time of a slot.
δ	Propagation delay.
W_0	The minimum CW.
$W_{m'}$	The maximum CW.
τ	The transmission probability of a station at the beginning of a slot time.
$\overline{W}$	The average contention window.
P_c	The collision probability of a transmission in the considered time slot when all the stations have the same data rate.
T_{idle}	The duration of idle slot
$T_{s,j}$	The duration of a successful transmission with data rate R_j.
$T_{c,j}$	The duration of a failed transmission that the lowest data rate among all collided stations is R_j.
P_{idle}	The probability that no transmission in a slot time.
$P_{s,j}$	The probability that a station transmits successfully with data rate R_j.
$P_{c,j}$	The probability that a collision transmission happened with the lowest data rate R_j among the transmitting stations.
T_{DIFS}	DCF interframe space time.
T_{SIFS}	Short interframe space time.
T_{PHYhdr}	Transmission time of PHY header.
T_{data}	Transmission time of MAC frame.
T_{ACK}	Transmission time of ACK frame.
N	The number of total nodes in the multi-rate WLAN, including wireless stations and the AP.

In a multi-rate WLAN, σ denotes the time of a slot, which is related to the physical modulation. The duration of a successful transmission T_s and a failed transmission T_c vary according to the data rate applied. According to the IEEE 802.11 standard of binary exponential backoff scheme, the contention window of each transmitter could be expressed by

$$(1)\ W_i = \begin{cases} 2^i W_0, & i \le m \\ W_m = 2^m W_0, & i > m \end{cases}$$

Where W_0 and W_m are the minimum (CW_{min}) and the maximum (CW_{max}) contention window respectively. The value of retransmission number m is 7 (ShortRetryLimit) when the frame length is less than the RTSThreshold, while the m is 4 (LongRetryLimit) when the frame length is longer than the RTSThreshold. Assume that each station with frames to transmit all the time and the media is ideal without transmission error. We also assume that the backoff time of each station to compete for the channel access is geometrically distributed. Based on geometric densities, the probability that there are x failures of Bernoulli trails before the first success is

$$(2)\ P(X = x) = (1-\tau)^{x-1}\tau, \quad 1 \le x \le \infty$$

The average contention window size $(\overline{W})$ is determined by the expected value of random variable X, and thus we have

$$\frac{\overline{W}+1}{2} = \sum_{x=1}^{\infty} x\tau(1-\tau)^{x-1} = \frac{1}{\tau} \qquad (3)$$

Since the backoff time is uniformly distributed over $\{0, \overline{W}\}$, the average contention window size is

$$\overline{W} = \begin{cases} \dfrac{(1-P_c)W_0 + P_c(1-P_c)2W_0 + \cdots + P_c^m(1-P_c)2^m W_0}{1-P_c^{m+1}}, & m \le m' \\ \dfrac{(1-P_c)W_0 + \cdots + P_c^{m'}(1-P_c)2^{m'}W_0 + P_c^{m'+1}(1-P_c)2^{m'}W_0 + \cdots + P_c^m(1-P_c)2^{m'}W_0}{1-P_c^{m+1}}, & m > m' \end{cases} \qquad (4)$$

By equation (3) and (4), we obtain

$$\tau = \frac{2}{\overline{W}+1} = \begin{cases} \dfrac{2(1-2P_c)(1-P_c^{m+1})}{W_0(1-P_c)(1-(2P_c)^{m+1}) + (1-2P_c)(1-P_c^{m+1})}, & m \le m' \\ \dfrac{2(1-2P_c)(1-P_c^{m+1})}{W_0(1-P_c)(1-(2P_c)^{m'+1}) + (1-2P_c)(1-P_c^{m+1}) + W_0 2^{m'} P_c^{m'+1}(1-2P_c)(1-P_c^{m-m'})}, & m > m' \end{cases} \qquad (5)$$

The collision probability P_c can be expressed

$$(6)\ P_c = 1 - (1-\tau)^{N-1}$$

Let S be the system saturation throughput, defined as the ratio of the expected value of the successfully transmitted sizes to the expected value of time slot durations. To simply the analysis, we only discuss the basic access. There are three different kinds of time slot duration in basic access mode which can be expressed as follows:

T_{idle}, the idle slot duration, $T_{idle} = \sigma$.

$T_{s,j}$, the duration which the channel is sensed busy by a successful transmission for the station with data rate R_j equals to $T_{DIFS} + (T_{PHYhdr} + T_{data} + \delta + T_{SIFS} + T_{PHYhdr} + T_{ACK} + \delta) \times Q_j + (Q_j - 1) \times T_{SIFS}$, where $Q_j = \left\lceil \frac{R_j}{R_1} \right\rceil$.

While the successful transmission duration for AP is

$T_{s,AP} = T_{DIFS} + (T_{PHYhdr} + T_{data} + \delta + T_{SIFS} + T_{PHYhdr} + T_{ACK} + \delta) \times Q_{AP} + (Q_{AP} - 1) \times T_{SIFS}$, where $Q_{AP} = [n_1 + \frac{R_2}{R_1} \times n_2 + \frac{R_3}{R_1} \times n_3 + \cdots + \frac{R_m}{R_1} \times (n_m - 1)]$.

$T_{c,j}$, the duration due to collision and is equal to the transmission time for the station with the lowest data rate R_j among the concurrent competing nodes, i.e. $T_{c,j} = T_{DIFS} + (T_{PHYhdr} + T_{data} + \delta)$, where T_{data} is transmitted with data rate R_j. And $T_{c,AP} = T_{c,m}$.

Moreover, the corresponding probabilities for these different slots are listed as follows.

P_{idle} is the probability that no transmission occurs in a time slot. $P_{idle} = (1 - \tau)^N$

$P_{s,j}$ denotes the probability of a data frame that is transmitted successfully by a station at data rate R_j and $P_{s,j} = n_j \tau (1 - \tau)^{N-1}$. Similarly, the successfully transmission probability for the AP is $P_{s,AP} = \tau (1 - \tau)^{N-1}$.

$P_{c,j}$ represents the probability that two or more nodes, in which the slowest data rate of the nodes involved is R_j, collided at the same slot. The calculation is divided into two cases. The first is that there is only one node with data rate R_j and at least one node with a higher data rate than R_j. The other is that there are two or more nodes with the same data rate R_j transmitting simultaneously. Thus we have

$$P_{c,j} = \left\{ n_j \tau (1 - \tau)^{n_j - 1} \left[1 - (1 - \tau)^{\sum_{j=i+1}^{m} n_j} \right] + \sum_{j=2}^{n_j} \binom{n_j}{j} \tau^j (1 - \tau)^{n_j - j} \right\} \prod_{j=1}^{i-1} (1 - \tau)^{n_i}$$

And $P_{c,AP} = P_{c,m}$.

We assume that each data packet has the same length L. When a node with data rate R_j completes a successful transmission, the transmitted packet size is $Q_j \times L$ for a station and $Q_{AP} \times L$ for AP respectively. Finally, the saturation throughput for the proposed DAT in a multi-rate WLAN with basic access can be expressed as

$$S = \frac{(\sum_{i=1}^{m} P_{s,i} \times Q_i \times L) + (P_{s,AP} \times Q_{AP} \times L)}{P_{idle} \times \sigma + (\sum_{i=1}^{m} P_{s,i} \times T_{s,i} + P_{s,AP} \times T_{s,AP}) + (\sum_{i=1}^{m} P_{c,i} \times T_{c,i} + P_{c,AP} \times T_{c,AP})} \quad (7)$$

Then we validate our DAT model by comparing the analytical results with simulation results. Specifically, we simulate and analyze the total system saturation throughput in an IEEE 802.11b environment, which has four data rates of 1, 2, 5.5 and 11 Mbps. The physical and MAC parameters used in simulation and analysis are listed in Table II.

Table II. IEEE 802.11b parameters used in simulations and analyses.

SIFS	10μs	Packet payload	8000bits
	20μs σ	PHY header	192bits
DIFS	50μs	MAC header	224bits
CWmin	32	ACK	112bits
CWmax	1024	(propagation delay)	1μs δ

In order to adopt the multi-rate transmission situations and prove the accuracy of the DAT model, we take three different multi-rate scenarios into consideration. The ratio of the number of wireless stations with different data rate 1, 2, 5.5, 11Mbps is set to be 1:1:1:1, 1:2:3:4 and 4:3:2:1 respectively. There is only one AP in all the three scenarios and the transmission data rate for the AP is 11Mbps. For example, if the ratio is 1:2:3:4 and the total number of wireless stations is 20 (the AP is not included), then 2 stations with 1 Mbps data rate, 4 stations with 2 Mbps data rate, 6 stations with 5.5 Mbps data rate and 8 stations with 11 Mbps data rate. The number of total stations ranges from 4 to 40 with step of 4 in the 1:1:1:1 scenario, and from 10 to 100 with step of 10 in the 1:2:3:4and4:3:2:1scenarios.

By the illustration of Figure 1 and Figure 2, we obtained that in the 1:1:1:1, 1:2:3:4 or 4:3:2:1 scenarios the analytical and simulation results of the total saturation throughput of the proposed DAT scheme are very close to each other. We also analyze the uplink and downlink throughput in the DAT mechanism and the results indicate that the uplink throughput is equal to the downlink throughput in all three scenarios.

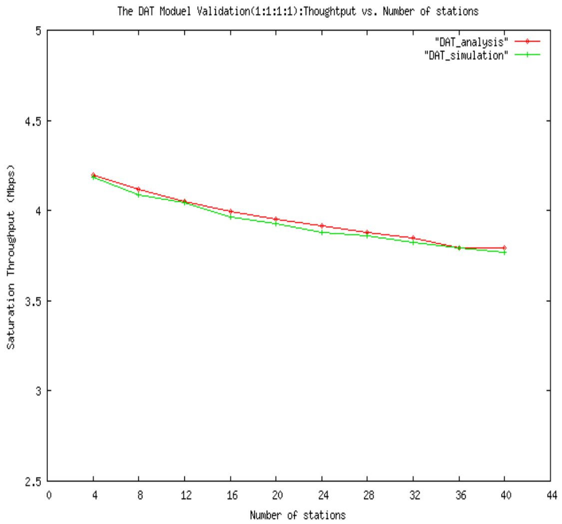

Fig.1 Model validations under the ratio of stations with different date rates (1, 2, 5.5, 11 Mbps) 1:1:1:1

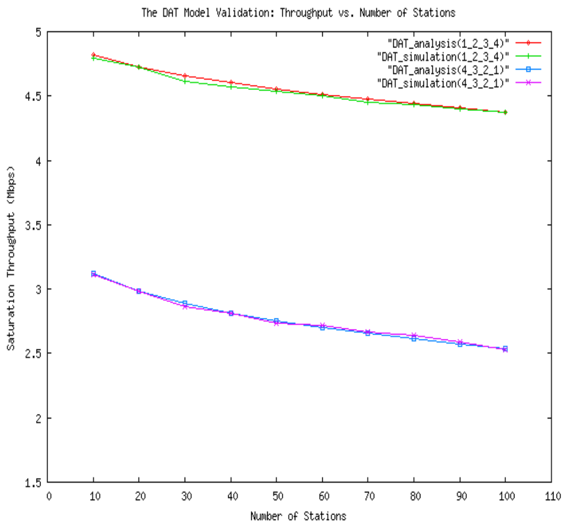

Fig.2 Model validations under the ratio of stations with different date rates (1, 2, 5.5, 11 Mbps) 1:2:3:4 and 4:3:2:1

4 Experimental Results

This section we compare the system performance of the proposed DAT scheme with legacy TXOP, MBT, AAP, CWD, and PSD mechanisms under various multi-rate scenarios. The simulation programs were written in C++ to simulate an IEEE 802.11b WLAN with infrastructure mode setting and operate with four data rates, i.e. 1, 2, 5.5 and 11Mbps. We only consider the basic access transmission mode. Each station and AP is assumed to have enough packets to send in order to obtain the saturated throughput in an error free medium. Also, there are no hidden or exposed terminals in the simulated environment. The physical and MAC parameters used in simulations are listed in Table II which is the same as the model validation settings.

Performing the simulations, we also take the three different multi-rate scenarios into consideration as the same in the section of throughput analysis and model validation. That is the 1:1:1:1, 1:2:3:4 and 4:3:2:1 scenarios.

Figures 3, 4, and 5 illustrate the simulation results of the total saturation throughput for the proposed DAT scheme and legacy TXOP, MBT, AAP, CWD, and PSD mechanisms. It is observed that the DAT scheme achieves the highest throughput of all the simulated mechanisms. In the three simulation scenarios we also find that the more the high data rate stations there are the more system throughputs can be achieved when the total number of the stations is fixed.

Figures 6, 7, and 8 present the uplink and downlink throughput with different mechanisms. It is clearly seen that the uplink and downlink throughput of the proposed DAT scheme are almost equal. The DAT scheme could not only obtain more system throughput than that of CWD and PSD mechanisms in a multi-rate environment but also provide the equal share of uplink and downlink bandwidth as the TXOP, MBT and AAP schemes.

Moreover, as mentioned in the introduction, the CWD mechanism improved the system performance more efficiency, but it has serious uplink/downlink throughput unfairness problem in all the simulation scenarios. The AAP scheme balances the uplink and downlink traffic very well, but the system transmission efficiency could not achieve a good performance. Interestingly, the AAP scheme could keep the performance almost the same no matter how many number of stations in the simulated scenarios.

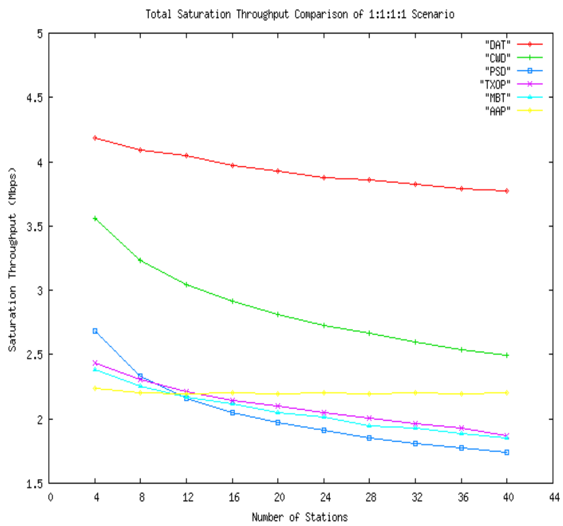

Fig.3 Total throughput comparison in 1:1:1:1 network

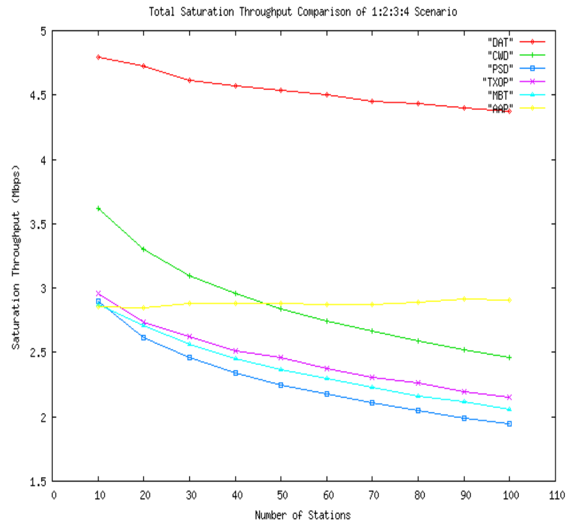

Fig.4 Total throughput comparison in 1:2:3:4 network

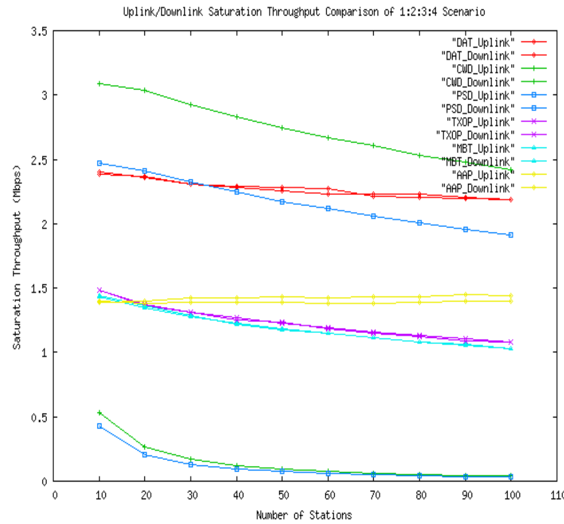

Fig. 7 The uplink and downlink throughput in 1:2:3:4 network

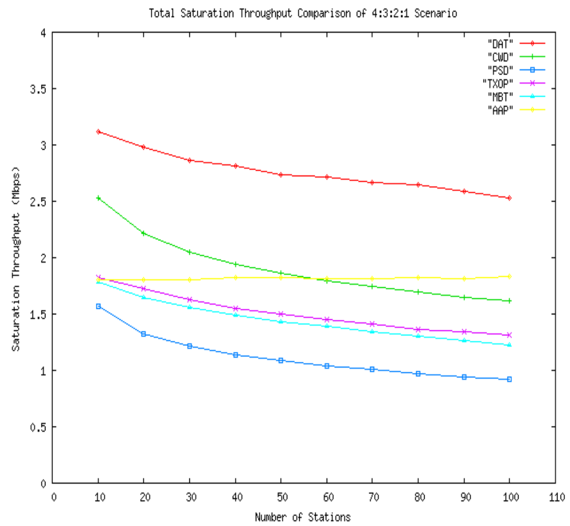

Fig.5 Total throughput comparison in 4:3:2:1 network

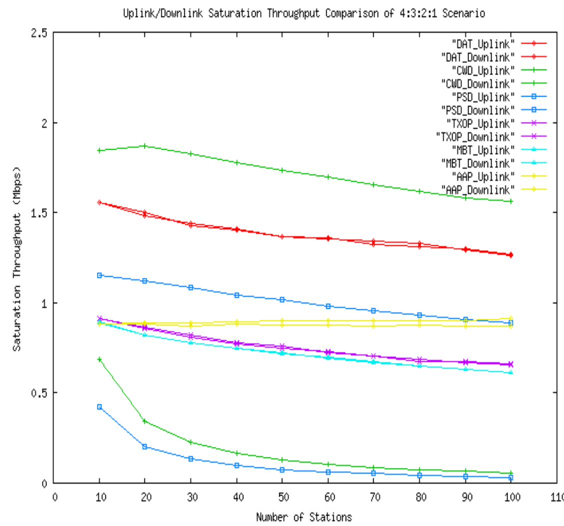

Fig.8 The uplink and downlink throughput in 4:3:2:1 network

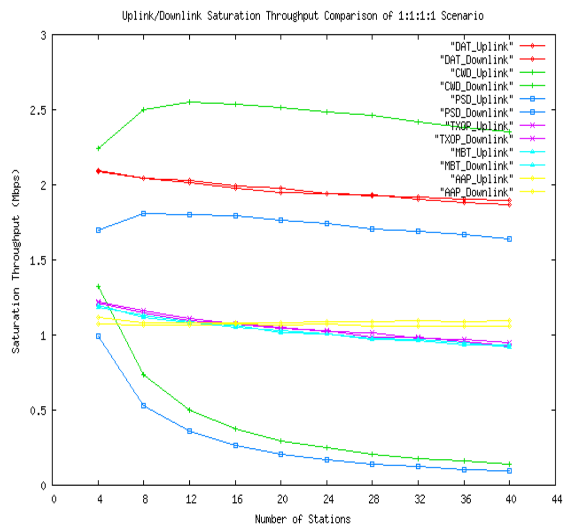

Fig.6 The uplink and downlink throughput in 1:1:1:1 network

Overall, the DAT scheme didn't modify the basic operations of IEEE 802.11 behaviors. Each station in the network still has the same probability to access the medium. We just let the stations with higher date rate to transmit more packets when it gets the right to access the channel. By simulations, we observe that it does work very well in improving system performance than the CWD and PSD mechanisms. Moreover, we let the AP to transmit traffic that is the summation of traffic each mobile station can send one time. It could balance the uplink and downlink traffic. As a consequence, the DAT scheme could both solve the uplink/downlink unfairness and the performance anomaly problems in a multi-rate WLAN and outperforms the previous mechanisms.

5 Conclusion

This paper has proposed a dynamic and adaptive transmission scheme (DAT) for both solving the asymmetric link sharing problem and the performance anomaly phenomenon in a multi-rate WLAN which operates in the infrastructure mode. Simulation results show that the DAT mechanism can provide higher performance in terms of throughput and uplink/downlink bandwidth share than previous related work. Taking a closer look at the experimental data, we observed that when the number of stations increases, the performance of the DAT scheme will degrade in all the simulation scenarios. How to improve the performance of the DAT scheme no matter how many stations in the multi-rate WLAN is a research goal for the future.

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