Collaborative Setting of RTS/CTS in Multi-Rate Multi-Cell IEEE 802.11 Wireless LANs

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***Abstract*—Despite the fact that the Request-To-Send/Clear-To-Send (RTS/CTS) protocol significantly reduces collisions and retransmissions due to the hidden node problem, it is well known that it adds considerable overhead specially with small payload packets. The IEEE 802.11 standard defined a manageable parameter, RTS threshold, above which a data packet should be preceded with RTS/CTS handshake. In this paper, we propose new dynamic criteria for setting the RTS/CTS mechanism. We believe that RTS/CTS settings should consider the characteristics of users' traffic, data rates, activities and locations. While most of the algorithms proposed for controlling RTS/CTS have been investigated under single transmission rate for all users, we evaluate our criteria in a multi-rate scenario. We validate our ideas using both synthetic and real traces as well as real experiments.**

I. Introduction

Nowadays, IEEE802.11-based Wireless Local Area Networks (WLANs) are being extensively deployed in many different locations. In a dense Extended Service Set (ESS) and due to the limited number of non-interfering channels that the IEEE 802.11 standard supports, some Access Points (APs) have to use the same channel which leads to mutual interference.

The Distributed Coordination Function (DCF) of the 802.11 MAC provides two access schemes: The Basic Access Scheme and the RTS/CTS Access Scheme. With the basic access scheme, a node wishing to transmit a data packet first has to sense the medium, and, if no activity is detected, the node waits a randomly selected additional period of time before it transmits if the medium is still free. If the receiving node receives the packet intact, it issues an ACK frame to confirm the reception of a data packet. The ACK frame completes the process if successfully received by the sender. The sender assumes a collision to have occurred if the ACK frame is not successfully received. The reason could be either the ACK was not correctly received or the data packet was not received intact. In this case, the data packet is transmitted again after deferring another random amount of time.

Collisions in WLANs mainly occur if nodes that can not hear each other, probably due to distance or an obstruction, transmit at the same time. Such nodes are referred to as "Hidden Nodes".

The 802.11 standard combats the hidden node problem by specifying an optional handshake protocol at the MAC layer known as RTS/CTS protocol. The RTS and CTS packets are small packets exchanged prior to transmission of data packets. For instance, in infrastructure based - WLANs a sender transmits a RTS packet to the AP which replies with a CTS packet. As all Basic Service Set (BSS) stations (STAs) hear the AP, they adjust their NAV (delay their transmission) based on duration information included in the RTS/CTS frames and refrain from sending. This allows the sending STA to transmit and receive a packet without any chance of collision. The major drawback of the RTS/CTS protocol is the additional overhead to the WLAN due to the temporary reservation of the wireless channel. Therefore, it is recommended to be exchanged just for large packets, which consumes large bandwidth if retransmitted.

Most of the studies on RTS/CTS have focused on the total throughput performance in the whole WLAN. Individual users' perspectives are not usually considered. Additionally, most of the previous investigations on the effectiveness of RTS/CTS have used similar transmission rates for all users. Since the collision duration and re-transmission time depend on the used transmission rates for data packets, the impact of re-transmissions and collisions on self and other users depends on the individual employed physical rates and not only on the size of retransmitted packets.

A. Paper Contribution

This paper proposes two criteria for controlling the RTS/CTS signaling based on detection of hidden node-pairs and QoS measurements utilizing the 802.11k standard. While previous studies evaluated the efficiency of RTS/CTS mechanism with synthetic traffic, our evaluation process is based on synthetic and realistic WLAN traces, and real experiments.

The remainder of this paper is organized as follows: Section II discusses the related work. Section III describes the assumed system model. In Section IV, we present and discuss our proposed criteria for controlling the RTS/CTS. Finally, we evaluate the performance of the proposed ideas in Section V before we conclude the paper in Section VI.

II. State of the Art

The RTS/CTS protocol is an attractive issue for many researchers. Reference [1] has studied the effect of the hidden node problem on the performance of 802.11 Ad hoc WLANs. The results have shown that the RTS/CTS mechanism improves the WLAN throughput as the number of hidden nodes exceeds 10% of the total number of nodes. The impact of the RTS threshold on the performance of 802.11 MAC protocol in Adhoc networks has been investigated in [2]. The authors conclude that the the number of nodes that share a channel is the factor that RTS threshold should be based on and not only the packet length. Nevertheless, the paper recommends to always enable RTS/CTS. Reference [3] presents a real time algorithm for updating the RTS/CTS threshold to enhance the performance of IEEE802.11e WLANs that employ the EDCA MAC protocol. The authors recommend to update the RTS threshold according the number of transmission attempts as well as the number of nodes in the BSS. Another study on the self-tuning of RTS/CTS can be found in [4]. The setting of the threshold depends on delay estimations. Also, the work in [5] proposes a dynamic mechanism for setting the RTS/CTS threshold based on estimation of the successful transmission probability of packets. The main shortcoming of [3],[4], and [5] is that the decision depends on packet loss rate, which is in fact depends on wireless channel conditions and not only on interference from other nodes. The impact of RTS/CTS mechanism on throughput performance has been investigated in [6]. The results have shown that the mechanism might block some successful transmissions in the network. However, the study and the analysis were limited to specific configuration of two APs and three nodes. A further study on the impact of RTS/CTS on transmissions is published in [7]. The paper concluded that the problems introduced by RTS/CTS can sometimes be more than its positiveness in solving the hidden node problem.

III. System Model

We consider a standard ESS 802.11 WLAN. The WLAN is composed of ***N*** BSSs and ***M*** users/nodes. All APs are connected to a single distribution system (DS) which connects them to the Wide Area Network (WAN). APs provide communication services to the ***M*** users that reside within their coverage area. At any time instant, a user is associated to a single AP. At the MAC layer, APs and users are assumed to employ the DCF mode with CSMA/CA channel access protocol. Users exchange data packets with the wired network via APs. A transmitting node dynamically adapts its transmission rate. Due to the lack of non-interfered channels that the 802.11 standard supports, some APs are assigned the same channel. The signal attenuation is mainly affected by path loss and fading. The coverage areas of APs are assumed to overlap.

IV. Dynamic Setting of RTS/CTS

Basically, the 802.11 standard defined a manageable parameter called *RTSThreshold* which determines when the RTS/CTS handshake should precede a packet.

From the discussion in the related work section, we see different conclusions of research activities. While some researchers concluded that the RTS/CTS should be enabled, some others recommended to disable it. As a matter of fact, the different views are due to the differences in the scenarios considered and the evaluation metrics used. Almost in all the work discussed in section II, the total throughput has been used as the performance evaluation metric. Individual perspective of users, the fairness among them have not been considered. Although a maximum aggregate throughput is an important goal, the impact of RTS/CTS mechanism on individual users is also of significant importance. It could happen that certain management policy very much improves the throughput of some users but degrades the throughput of many others. If one just observes the aggregate throughput, the impression would be that the algorithm is a good and efficient one but the fact could be that many other users become less happy with the new settings. This is due to the fact that the performance depends on many correlated factors like: The physical rates, number of users, traffic characteristics, location of users in the BSSs, and interference from neighboring BSSs. In some cases, enabling RTS/CTS might be useful albeit with packets of moderate lengths despite the overhead it adds. Also, there should exist some cases, where RTS/CTS should be turned off.

To this end, the impact of RTS/CTS on individual users and the overall performance is very much scenario-dependent and a function of numerous parameters.

A. RTS/CTS in Multi-Rate WLANs

In principle, the intuition behind the RTS/CTS packet length threshold defined in the 802.11 standard is that long packets consume long time if retransmitted due to collisions of hidden nodes transmissions. In a multi rate WLAN, this time is however a function of both packet length and the used transmission rate for data packets. Therefore, a better threshold that considers both parameters should be used. A node can easily anticipate the physical rate of the next packet from the recent history.

A common shortcoming of the cited work in section II and even some recent ones like [8], [9], [10] is the assumption of similar transmission rates of data packets for all nodes. The focus has been devoted to investigations of RTS/CTS impact on the achieved throughput since these handshake packets are transmitted using lower rate than data packets transmission rate. ***Since the cost of collisions depends on the used data rates, the efficiency of any algorithm that reduces the collision rate should be investigated in a multi-rate environment.*** To explain it more, the required time for re-transmitting a same packet at 1Mbps is 11 times greater than transmitting it at 11Mbps. Therefore, re-transmitting small packets (after collisions) at lower rates may consume considerable bandwidth and will indeed impact other users that employ high physical rates negatively due

to the long collision time periods, i.e worsening the well known Anomaly Problem [11]. ***Thus, intuitively, reducing the collisions and consequently re-transmissions at low physical rates improves the performance of high rate users which can not be observed when all users employ the same transmission rate.***
In [12], the authors proposed to use a threshold derived for the single BSS and homogeneous rate scenario in a multi-rate (heterogeneous) scenario.

B. Controlling RTS/CTS based on Detection of Hidden Node Pairs

A first criterion we propose for controlling the RTS/CTS setting is the number of hidden node-pairs in a BSS covered by an AP. A challenging issue is the detection of hidden nodes. The criterion benefits from the standarized reports defined in the IEEE 802.11k standard:

Criterion 1

- Each node monitors the transmissions in the BSS and reports the the average power received from each node to its AP. The IEEE 802.11k standard specifies the mechanisms that allow users and APs to exchange this information.
- The AP then constructs an Interference Map from which it determines the set of hidden node pairs by correlating the information received from nodes.
- Two nodes in a BSS are assumed to be hidden from each other (hidden pair) if both report very small reception power from each other or they do not hear each other at all.

Having this map, there are three options:

- **Option 1:** If the number of detected hidden node pairs is above a certain threshold, the AP instructs its associated users to use RTS/CTS prior to data packet transmissions.
- **Option 2:** The AP instructs all active nodes whose transmissions do not reach some other active nodes to enable RTS/CTS. With this option, it is expected that some nodes that are close to the AP will be requested to use RTS/CTS since such nodes normally employ high rates and their coverage is limited. If such nodes use RTS/CTS: (i) They will avoid collisions with low rate nodes whose retransmissions take time. (ii) In the meanwhile the performance of far nodes as well as the fairness among all users will improve.
- **Option 3:** The AP instructs only detected hidden node pairs to use RTS/CTS.

C. Collaborative setting of RTS/CTS

Multiple BSSs that use the same channel may influence the operation of RTS/CTS. To illustrate this, consider the two BSSs example of figure 1. According to the standard, user S2 will not be able to respond to the RTS sent by its AP 2 until the exchange data and ACK between user S1 and AP 1 completes. However, the RTS from AP 2 will mislead users S3 and S4 which think that a data transmission is taking place and hence prevented from accessing the channel and consequently cause throughput degradation.

The motivation for the collaborative criterion we propose in this section is the very high dependency of the achieved performance with or without RTS/CTS exchange on the scenario (i.e location of users' in the BSSs, interference from neighboring BSSs, users' traffic characteristics and activity levels, etc.) and the complexity of inferring this performance apriori. With the collaborative approach and based on some policy, neighboring BSSs that operate over the same channel could decide jointly whether their users should use RTS/CTS based on QoS measurements.

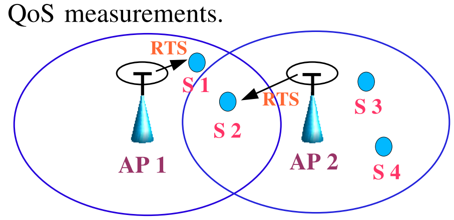


Fig. 1. Negative influence of RTS/CTS in Multi-Cell WLANs

Criterion 2

- Each AP in a BSS shall instruct the nodes it accommodates to disable RTS/CTS, observe, measure and quantify their current QoS for some time period.
- At some time instant, all nodes shall use RTS/CTS prior to data packets and start to observe their QoS over a testing phase the length of which shall be defined a priori.
- At the end of the test period, nodes report the QoS measurements to their respective APs. Measurements of each node may be concluded in one number.
- APs share measurement information or their local recommendations based on the testing phase results.
- One AP processes the measurements and decides whether RTS/CTS shall be used based on probable improvement in the QoS after using the RTS/CTS mechanism. The decision is then signaled to other BSSs which distribute it to the users.
- After some time period, the current status of RTS/CTS is inverted and the testing takes place.
- In order to avoid excessive signaling and processing, the periodicity of the testing phase can be adaptively selected based on the difference between the most recent decision and the previous one.
- The potential metrics for the decision could be: Throughput, fairness or both.

Signaling between Access Points As stated previously, neighboring BSSs can jointly and cooperatively decide on the setting of RTS/CTS based on measurements. However, the implementation of such policy requires a signaling protocol. The protocol shall enable APs to exchange their recommendations or votes to the decision. In this subsection we present a brief description of such protocol.

Each AP shall be able to trigger the protocol if the local policy decides so (based on increased retransmission rate, for example). The initiating AP takes a role of a master and requests other neighboring APs to enter the testing phase at some time instance. Receiving APs could accept or reject participation. The response shall be sent in a message to the master. Based on the received responses, the master expects the votes from participating APs after some time period. APs that accept participation shall start the test phase at the time instance included in the request message. They are supposed to send their ”own” votes after the testing phase in a notification message. After receiving notifications from all participating APs, the master AP shall inform them of the final decision and schedule the next testing phase.

Under the assumption that APs belong to the same administrative domain, APs can exchange the protocol messages via the backbone network to which the APs are attached. Although the protocol procedure requires some synchronization, this synchronization is not tough and can also be achieved via the backbone network.
Note:The main drawback of Criterion 2 is the potential performance degradation during the testing phase and the requirement to enable or disable the RTS/CTS for all nodes which may negatively impact nodes that are not hidden from each other. For the sake of space limitation, we point out the idea of potential improvement of a collaborative approach. If APs share interference map information, The set of hidden and active nodes can be easily identified. Hence, only hidden node pairs are asked to enable RTS/CTS.

V. Performance Evaluation

In this section we evaluate the performance of the proposed criteria for controlling the RTS/CTS use. We have conducted detailed simulation experiments using the NCTUns simulation package [13]. We use both synthetic and real traces for our evaluation. Evaluation using synthetic traces gives intuition about how the performance gain varies with different parameters. Simulations with realistic traces provide us the knowledge of how really the performance of our policy looks like if it is deployed in a realistic network. We used the SIGCOMM 2001 and SIGCOMM 2004 traces (available from [14]) in the following way: Using CoralReef Software [15], we extracted users flows from the dump file. We selected the flows of 100 different users during 1 hour. We used the total number of bytes, number of packets of each flow to compute an average packet length.
In order to better validate the simulation results, we also conducted some real experiments in an indoor office environment. The experiments exploit the impact of collisions between low rate packets from hidden nodes and high rate packets on throughput.

A. Simulation Scenario

The simulation scenario comprises 10 BSSs and 100 wireless users. Three channels are assigned to the 10 APs based on the legacy optimal channel assignment approach (i.e Adjacent APs are configured on different channels). All nodes implement the 802.11b technology. The traffic was generated with the **stg** tools that come with the NCTUns simulation package. To consider more realistic conditions, the transmit power of all nodes was set to 15dBm and the communication range is set by the NCTUns based on the physical transmission rate and transmit power. A sender selects the physical transmission rate based on the distance to the receiver.A Rayleigh fading model provided by the NCTUns simulator was used. For the path loss we have used a two ray ground reflection model.

B. Performance Evaluation Metrics

For performance evaluation, we use per second throughput, packet delay, and fairness among users (STAs) captured by Jain’s fairness index [16].

C. Real Experimentation Set-up

We used four Laptops equipped with WPN511 RangeMax WLAN Adapters from Netgear. Using MADWiFi driver, one laptop is configured in the AP mode. The second one is placed close to the AP in an office and the third laptop is placed far from the AP in another office. Through transmission power control, we hide the second and third laptops from each other, but assured that each one can connect to the AP. Using **stg** traffic generator, both laptops send data packets to the AP which records the throughput of the received packets from each in a separate log file. While the far laptop is expected to utilize low transmission rate, the one close to the AP is expected to use high transmission rate due to the good signal level it receives from the AP. The experiment duration is three minutes. During the first minute, both transmitting laptops use the basic access scheme (i.e RTS/CTS is off). During the second minute, both laptops signal RTS/CTS prior to every data packet while during the third minute only the far laptop uses RTS/CTS. The experiment is repeated 40 times in different times of a day. In another experiment and in order to observe the percentage of retransmitted packets from the close laptop, the far laptop sends data packets to the AP and the close laptop copies a file to the AP using the **netcat (nc)** utility with the TCP protocol. A fourth laptop is configured in the monitor mode and used to sniff packets transmitted by the close laptop. The Ethereal - Network Protocol Analyzer has been used for this task.

D. Evaluation Results

1) Synthetic Traffic: We firstly distributed users randomly in small areas around the 10 APs (i.e low probability of hidden users). Figure 2 plots the aggregate throughput of all users with large packets. The figure shows that even for large packets the throughput performance may significantly degrade with RTS/CTS enabled. This is due to the absence of hidden nodes in such configuration and consequently the low collision rate. Hence, algorithms that suggest to always enable RTS/CTS may sometimes degrade the system performance even with large packets.

Now we compare the throughput performance of **Criterion 1 - Option 2** and **Criterion 2** presented in sections IV-B and

IV-C with three cases proposed in the literature: always enable RTS/CTS, always disable RTS/CTS, and enable RTS/CTS for packets above an RTSThreshold (set to 700 Bytes). With the collaborative criterion (**Criterion 2**), APs that operate over the same channel instruct their users to enable/disable RTS/CTS if the new setting (during testing) improves the overall throughput by at least 10%. STAs transmit packets of different lengths drawn from an exponential distribution with 1500, 50, 2000 bytes mean, minimum and maximum respectively. The packet inter-arrival time is set to 0.01 seconds. Figure 3(a) plots the average throughput of 30 different topologies, whereby in each case all STAs were randomly distributed in the coverage area of APs. We make the following observations: **(i)** RTS/CTS should not be completely disabled. **(ii)** The 700 bytes RTSThreshold criterion achieves better performance than the case in which RTS/CTS was always enabled. **(iii)** Furthermore, the collaborative criterion outperforms **Criterion 1**. This is because the collaborative criterion bases the setting of RTS/CTS on the potential improvement of the total throughput of all STAs. Note that with our criteria, RTS/CTS was set off before second 85 and the new settings take place after second 85.

The throughput fairness index curve of figure 3(b) shows the improvement in the fairness among all users before and after enabling RTS/CTS (after second 85).

Now, we show the necessity of evaluating the efficiency of RTS/CTS control criteria in multi-rate environment. We plot the throughput and delay performances of all users that employed each rate in figure 4. The results show that aggregate throughput of low rate users improved significantly when RTS/CTS is enabled. However, for the 11Mbps users, small improvement has been observed after using RTS/CTS. Meanwhile, the delay performance of each group of users has been considerably decreased after using RTS/CTS. For single rate WLANs, figure 5 show the throughput and delay performances. It is clear that when all users employ 11Mbps transmission rate, both throughput and delay performance degrade after enabling RTS/CTS while they greatly improve when low rates are employed. From these results, we conclude that the overall performance with RTS/CTS depends also on the employed physical rates for data packets.

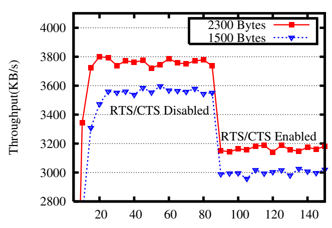
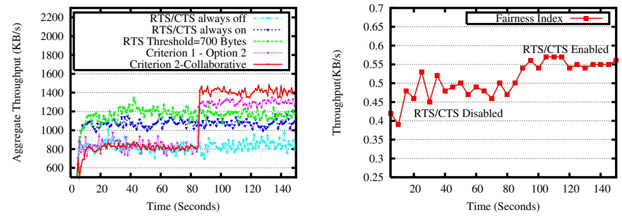


Fig. 2. Aggregate Throughput Performance of all users for large packets and 0.01 seconds inter-arrival time.

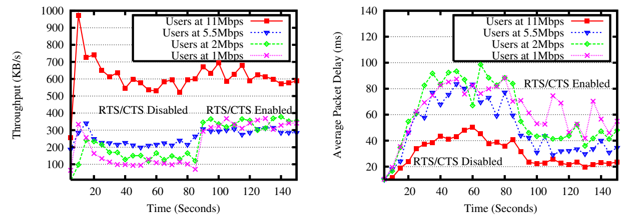
2) Real WLAN Traces: In this part we present the results of simulation experiments performed with realistic WLAN traces and focus on the collaborative criterion. Figures 6(a) and 7(a) depict the throughput performance of the collaborative criterion with realistic traces from SIGCOMM 2001 and SIGCOMM 2004 respectively. We make the following observations on both scenarios: **(i)** The collaborative criterion tracks the situations in which enabling or disabling RTS/CTS is beneficial. It outperforms the 700 bytes RTSThreshold criteria. **(ii)** Although a degradation in performance may occur before and during the testing phase (not very clear since the scale is in minutes and the measurement duration was set to 5 seconds), this should not be harmful and is better than always enabling or disabling RTS/CTS which may degrade the performance for long time. **(iii)** Observing the retransmission curves shown in figures 6(b) and 7(b), it is clear that disabling RTS/CTS is accompanied with a decrease in the number of retransmissions. This indicates that a change in retransmission rate could be used as a trigger for testing whether enabling or disabling RTS/CTS may improve the situation.



(a) Comparison Results.

(b) Fairness among all users before and after using RTS/CS.

Fig. 3. Comparison between our dynamic RTS/CTS setting and some common approaches.

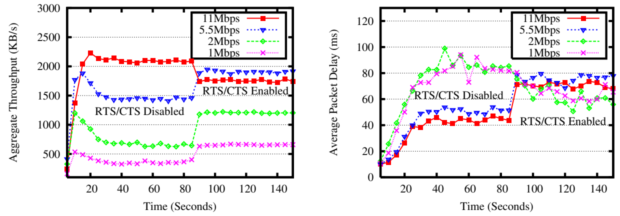


(a) Throughput

(b) Delay

Fig. 4. Impact of RTS/CTS on Throughput and Delay of Heterogeneous Rate Users with 1500 Bytes packets and 0.01 seconds inter-arrival time.

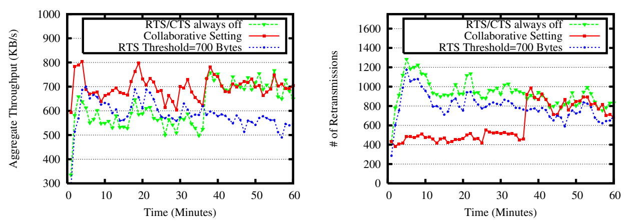
3) Real Experimental Results: With the experimental setup presented in section V-C, figure 8(a) shows an improvement in the throughput performance when both users/laptops have enabled RTS/CTS (between second 60 and second 120). The figure also shows that the maximum throughput was achieved when only the low rate user uses RTS/CTS (during the last 60 seconds). On the other hand, figure 8(b) shows the throughput performance of the two users when both utilize the same data rate. Conversely, these results reveal that the RTS/CTS may degrade the performance if used. Additionally, figure 9 plots the percentage of TCP retransmissions from the user that is close to the AP during a real file transfer experiment using **netcat (nc)** utility. The sniffer captures packets for 1 minute.



(a) Throughput (b) Delay

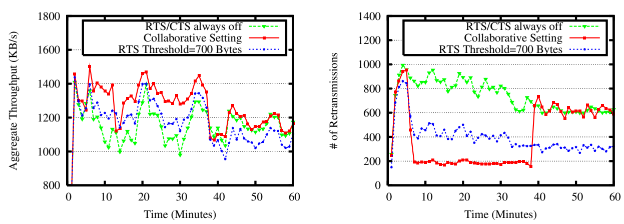
Fig. 5. Impact of RTS/CTS on Throughput and Delay of Homogeneous Rate Users with 1500 Bytes packets and 0.01 inter-arrival time.

The experiment is done when the far laptop transmits with and without RTS/CTS. The results show that large amount of bandwidth is wasted when the far user does not use RTS/CTS. This is due to retransmissions caused by collisions whose duration depends on the used low rate by the far user. These results are in agreement with the conclusion of the simulation results concerning mixed rate scenarios.



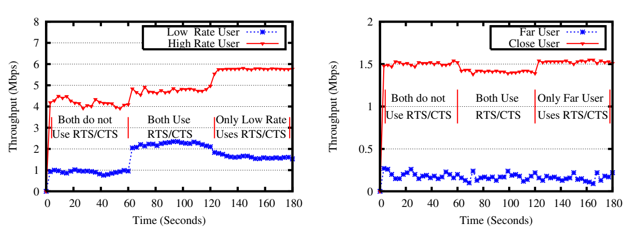
(a) Throughput (b) Retransmissions

Fig. 6. Performance of Collaborative Criterion with Real WLAN Traces from SigComm2001.



(a) Throughput (b) Retransmissions

Fig. 7. Performance of Collaborative Criterion with Real WLAN Traces from SigComm2004.



(a) Heterogeneous (b) Homogeneous

Fig. 8. Impact of RTS/CTS in Heterogeneous and Homogeneous Rate Scenarios.

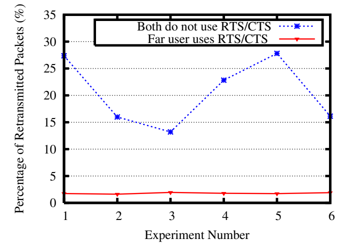


Fig. 9. Impact of RTS/CTS on the TCP Retransmission for real file transfer in heterogeneous rate scenario.

VI. Conclusions

In this paper we proposed new criteria for dynamically setting the RTS/CTS mechanism. The paper presents simulation and real experimental results obtained from a set of conducted experiments. The following conclusions can be drawn from the experimental results: First, the RTS/CTS may be dynamically enabled or disabled based on QoS measurements and joint agreement among APs. Second, since in reality WLAN users employ different data rates and since the collision time is bounded by the time of the packet transmitted at low rate, the impact of collisions and consequently the gain from their reduction on self and others depend on the used rates.

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