Dynamic Sensitivity Control Algorithm leveraging adaptive RTS/CTS for IEEE 802.11ax

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***Abstract*— The need for higher data rates and improved coverage has led to massive and uncoordinated deployments of IEEE 802.11 based WLAN Access Points in geographically limited areas that has resulted in increased interference with reduced area throughput. Recently, the IEEE 802.11 working group has continued efforts to cater the aforementioned problems by creating the IEEE 802.11ax Task Group, TGax (which aims to improve performance in dense environments). TGax has been actively involved in the design of Clear Channel Access (CCA) modification schemes, where Dynamic Sensitivity Control (DSC) algorithm has been proposed as one of the key innovative technologies to increase the spectral reuse. However, DSC scheme has drawbacks: increase in frame collisions as well as hidden node count. In this paper, we propose the combined usage of DSC along with an intelligent mechanism to enable RTS/CTS on selected stations within densely deployed WLAN network. We present methods to select stations for 4-way handshake and indicate considerable gains (up to 60%) when a network utilizing the aforementioned method is compared with legacy IEEE 802.11 operation.**

I. Introduction

The need for improved performance and efficient methods to share the limited resources within IEEE 802.11 based Wi-Fi networks has resulted in extensive research being done on spatial reuse, interference and efficient resource sharing. While the new IEEE standards (i.e. IEEE 802.11n and IEEE 802.11ac) were developed with the intention to improve the physical rate, mitigation of increased interference incurred due to the existence of many AP and non-AP devices has not been addressed in any of the current WLAN standards. For this particular reason, the IEEE P802.11 WG is contemplating the design of a new standard that aims to revamp the legacy Physical and MAC layer protocols so as to improve user experience (in terms of fairness, delay and throughput) within high density networks. This proposed amendment intends to significantly increase spectral frequency reuse and to manage interference from neighboring OBSS.

In legacy IEEE 802.11, Distributed Cordination Function (DCF) is the default/dominant channel access mechanism, that defines two access mechanisms; the basic two way handshake mechanism and the optional reservation scheme based on four-way handshake (called RTS/CTS). In both the aforementioned mechanisms, Physical Carrier Sensing (PCS) is used in a distributed way over each node to decide the availability of shared medium. A threshold, called Carrier Sensing Threshold (CST) is used, where a channel is considered to be busy if the strength of the received signal is greater than the foregoing threshold. In current IEEE 802.11 standards, this threshold is assigned a fixed value, which leads to well investigated hidden and exposed nodes problems. While hidden nodes are the main cause of collisions in WLAN networks (due to transmission of nodes that are present in each others carrier sensing range and are unable to hear each other due to obstruction or distance), the exposed node problem has been found to have greater implications for dense deployments (where stations are unnecessarily silenced due to over protected PCS method).

In order to build on the argument that stations may end up always assuming channel to be busy by utilizing fixed CST value, even though the possibility of multiple concurrent transmissions exists (with small increase in number of collisions), the IEEE 802.11ax amendment formally aims to embrace the idea of including dynamic CST modification (also referred to as CCA modifications) to allow each station to modify the carrier sensing criteria using local information.

TGax has been actively involved in the design of CCA modification schemes, where Dynamic Sensitivity Control algorithm [1] has been proposed as one of the key innovative technologies that can increase the overall throughput up to 20% when used with optimal channel selection [2].

One of the drawbacks of allowing multiple concurrent transmissions to coexist in geographically limited area is the increase in hidden nodes, which results in increase of system level Frame Error Rate (FER) [3]. The hidden node problem can get further aggravated for stations within high density networks due to obstacles, transmit power, location and mobility.

In order to combat the hidden node problem (so as to reduce collision probability), the legacy IEEE 802.11 has already devised the optional RTS/CTS access mechanism, where Ready to Send (RTS) and Clear to Send (CTS) frames are exchanged prior to transmission of data frames. However, this optional feature has not been adapted in most of the implementations of the WLAN standard due to the additional overhead associated with temporary reservation of the shared medium (i.e. for small data frame size used, this overhead becomes significant). Thus, the problems associated with RTS/CTS method counterbalance its positive aspects and thus an adaptive mechanism is required to enable RTS/CTS through a selective approach.

A. Contributions

Since conventional interference management techniques, when applied intelligently to dense deployments, can also ease the overall network conditions, in this paper, we propose the adaptive utilization of RTS/CTS mechanism along with DSC scheme so as to neutralize the negative effects of CCA modifications. The IEEE 802.11ax has already shown keen interest in including a method that allows an AP to remotely enable RTS/CTS for any of its associated stations. With the help of system model description and simulation results, we give substance to the utilization of RTS/CTS along with DSC

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and even indicate increase in performance efficiency over the already proved DSC scheme. Another motivation to study the foregoing combination is because a major drawback of RTS/CTS scheme is already overcome by the usage of larger frame size (e.g. frame aggregation) available in the new IEEE 802.11 amendments.

In other words, our aim in this work is not to design and evaluate a specific algorithm or heuristic to be implemented in future IEEE 802.11ax devices, but to study the potential benefits of combining intelligent CCA adaptation and uplink RTS/CTS control, leveraging new mechanisms under the consideration of the IEEE 802.11 TGax. To the best of our knowledge, the evaluation of the foregoing mechanism has not been presented in literature.

The remained of the paper is orginized as follows. In section II, we emphasize the rational behind our proposition and define a system model over which the evaluation of the proposal is done. In section III, the details of simulation environment are presented. In section IV, the performance evaluation of the proposed framework is presented. In section V, we summarize the related work.

II. System Model

As highlighted in TGax specification framework document [4], this new amendment intends to define a mechanism by which an AP can configure the use of RTS/CTS for each associated non-AP station. In [5], the authors highlight the possible mechanism through which an AP can control the RTS/CTS policy for the associated stations. We build our propositions on the aforementioned principles.

The legacy IEEE 802.11 standard has defined a configurable parameter called RTS Threshold (RT), that is used to enable and disable the RTS/CTS handshake for each station. If the length of frame to be transmitted is greater than the assigned RT, the four-way handshake is initiated. Traditionally, the RT value was always set to a very high value so as to disallow the usage of the RTS/CTS mechanism.

In this section, we illustrate methods through which we select certain number of stations within the network to utilize RTS/CTS. Different metrics (i.e. FER, Signal to Interference plus Noise Ratio (SINR), hidden node count, etc.) can be used as selection criteria. FER information is readily available over each station and thus can be used in the decision process. However, it is difficult to measure SINR in real system, especially when the intended and the interference signal arrive asynchronously. Furthermore, both FER and SINR are highly depending on the environment, where mobility and obstacles can induce random variations. Hidden node count at each station can also be utilized to initiate RTS/CTS method because most of the collisions occur due to transmissions from stations that are unable to hear each other. However, detecting hidden nodes at each station is not trivial.

In this paper, we use FER as well as hidden node count as the main criterion to enable and disable RTS/CTS. Intuitively, lower FER does mean less frame collisions, indicating a smaller number of hidden terminals. Using FER metric is a practical approach to the problem in hand. Hidden node count, on the other hand, is used to validate the concepts of increase in FER but can not be considered practically feasible solution.

We consider L APs and M non-AP stations associated to a single AP within each cell (i.e. we have total of $L \times M = N$ non-AP stations). All APs are assumed to be connected to a single distribution system (DS). Furthermore, the coverage area of the cells are assumed to overlap, where each non-AP station is only associated with a single AP. At the MAC layer, all stations utilize DCF-based channel access method, where the stations can opt to use basic or RTS/CTS mechanism. A transmitting station can dynamically adopt its Carrier Sensing Range by utilizing DSC algorithm (previously evaluated in [3]). Due to lack of non-overlapping channels, some of the APs are assigned same channels.

A. *Method 1*

In this method, we enable RTS/CTS mechanism on O (where $O \subset N$) number of stations based on the criteria that the FER of the selected stations is greater than FER_{Thresh} (i.e. a threshold based on the average FER of the network). All APs are assumed to be able to infer FER information of all associated stations (either by means of an explicit feedback, or through local estimations based on received frames [6]) over the duration of τ_c, where DSC is enabled for all non-AP stations. Figure 1 highlights the implementation details of the proposed method, where two separate instances of a network are operated in sequential manner. In the first step, the APs collect the FER information (f_i) of each station for a specific period. Afterwards, they collaborate to find the average FER (called $AvgFER$ in equation 1) within the network. Following equation is used to calculate the FER_{Thresh},

$$FER_{Thresh} = \delta \times AvgFER \tag{1}$$

where δ is assigned a fixed value. As shown in subsection IV-A1, δ = 0.6 provides the best performance. In the second step, this FER_{Thresh} is used by each AP to select an RT value for each associated station (i.e. AP activates RTS/CTS by transmitting specific RT values to the associated stations). The RT_i value set for each station by the AP can be explained by the following linear adaptation algorithm,

$$RT_i = \begin{cases} minRT_i, (f_i \geq FER_{thresh}) \\ maxRT_i, (f_i < FER_{thresh}) \end{cases} \tag{2}$$

where $minRT_i$ is a value that is less than the frame length used by a non-AP station that, in return, activates RTS/CTS for it and $maxRT_i$ has a value greater than the frame length, that disables RTS/CTS[1].

As an outcome of this method, a percentage of stations only employs the 4-way handshake mechanism based on their FER being ranked in the overall network. Figure 1 signifies the implementation detail of the foregoing method, where STA represents a non-AP station.

B. *Method 2*

The drawback of the previous method (i.e. Method 1) is the need for all the APs to collaborate in order to evaluate the $AvgFER$ of all the stations operating within the network.

On the contrary, in this method we maintain the distributed nature of each cell, where every AP selects a fixed percentage (i.e. η) of stations to enable RTS/CTS. The AP ranks the FER

[1] If all the non-AP stations utilize similar frame lengths, both $minRT_i$ and $maxRT_i$ can be assigned fixed values.

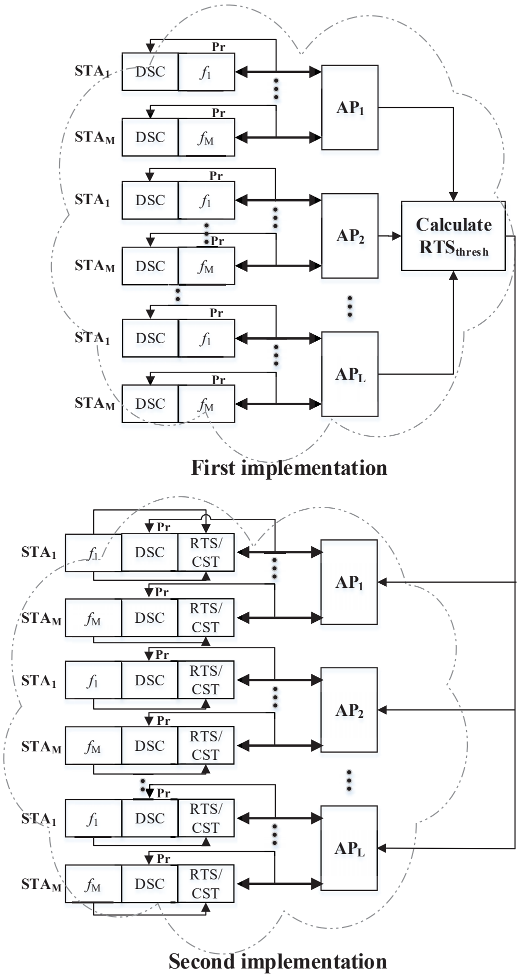


Fig. 1: Graphical representation of Method 1.

of associated stations and selects the percentage of stations that have the highest FER in descending order. The AP then assigns and transmits a specific RT_i value to each station which results in activation or deactivation of RTS/CTS for a station (i.e. RTS/CTS is enabled when RT of station is greater than the frame length used by it and vice versa).

C. Method 3

Since, by utilizing RTS/CTS method, we explicitly want to tackle the problems caused by hidden nodes, in this Method 3, we utilize hidden node count at each station as an enabling criteria. Even though, this method does require additional algorithm being implemented at the stations, we use it to compare with the FER based schemes presented in II-A and II-B.

At the beginning, each station shares the hidden node count information with its AP. All the APs then collaborate to select a percentage (i.e. γ) of stations to enable 4-way handshake. The selection process involves ranking the hidden node count for each station in descending order and to select stations that have highest number of hidden node count. Each AP then transmits a specific RT_i value for each associated station which results in activation or deactivation of RTS/CTS for a station (i.e. RTS/CTS is enabled when RT of station is greater than the frame length used by it and vice versa).

III. Simulation setup

We present a simulation-based study to evaluate the performance of IEEE 802.11 infrastructure network operated within a dense building apartment. We compare the performance when DSC was used within the network against the legacy IEEE 802.11, in which a constant CST threshold was set in every node.

In our simulations, we considered the scenario defined by the TGax in [7], consisting in a multi-floor residential building (see Figure 2). It consisted of 100 apartments and had the following specifications:

- 5 floors
- 2×10 apartments in each floor
- Apartment size: 10m$\times$10m$\times$3m
- Building type: Residential
- External wall type: Concrete with windows

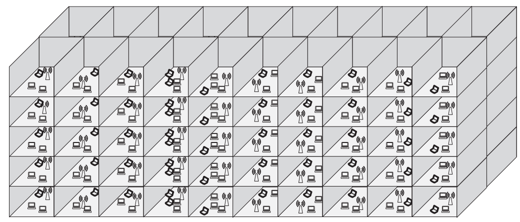


Fig. 2: Layout of dense deployment of IEEE 802.11 infrastructural network in residential building.

A single AP was randomly placed within the walls of each apartment. M (where $M = 5$) non-AP stations were placed around each AP randomly. Furthermore, APs selected channel 1, 6 and 11 randomly so that each channel was shared by 1/3 of the cells (i.e. $L = 30$ APs using the same channel). We focus our study on the use of 2.4GHz band because this band is more restricted in dense environments. The simulation was carried out using NS-3 network simulator in which Hybrid Building propagation loss model was used [8]. For the final calculated results, a large enough number of simulations were run in order to have small 95% confidence intervals. A large enough simulation time was chosen to disregard the transient time due to initial association between stations and APs. We considered uplink transmission[2], where each non-AP station was in saturation condition[3] (i.e. stations always have frames to transmit). Constant Bit Rate UDP flows were used on each transmitting node. It is important to mention here that the comparison between DSC and conventional IEEE 802.11 network was done under the exact same network conditions. The metrics used in our evaluation are: 1) aggregate throughput (total bytes correctly received by the receivers per second); 2) Frame Error Rate (FER); 3) Fairness (calculated according to Jains Fairness index [9]); 4) number of hidden nodes; 5) number of exposed nodes. For the hidden node analysis, we considered pair of hidden nodes (i.e. two nodes that are hidden from each other) as a single entry. This simplification was also

[2]We evaluate DSC over uplink transmissions because it is the worst case in terms of contention.

[3]Saturation is used to explore maximum capacity.

used for the exposed node count.

The description of Physical and MAC layer parameters used within our simulation are detailed in Table I.

TABLE I: Physical and MAC layer parameters for simulation.

Parameter	Values	Parameter	Values
Wireless Standard	IEEE802.11n	Packet size	1000, 1600, 2302Bytes
Frequency band	2.4GHz	Trasmission power of STA	16dBm
Physical transmission rate	7.2Mbps	Antenna gain	1dB
Propagation loss model	Hybrid buildings propagation loss	Noise figure	7dB
Wall penetration loss	12dB	Initial CST	-80dBm
Floor penetration loss	17dB	Auto Rate Fallback (ARF)	not used
Guard interval	Short	Data preamble	Short
Channel width	20MHz	Beacon Interval	100ms
Aggregation	not used	RTS/CTS	Selectively enabled

In our previous works [3], we provided a set of recommended values for DSC (MarginSTA = 20dB; RSSIDec = 6dB). Those values were found to produce a good balance between the benefits of DSC and its drawbacks. Furthermore, $UpperLimit$ is set to $-40dBm$ and $LowerLimit$ is set to $-82dBm$ for every non-AP station that utilizes DSC. $2s$ of $UpdatePeriod$ is used within the DSC algorithm.
Following equation 2, the $minRT$ is set to 200 (i.e. a fixed value below the data frame size) and $maxRT$ is set to 999999 (i.e. a fixed value above the data frame size).

IV. Simulation Results and Discussion

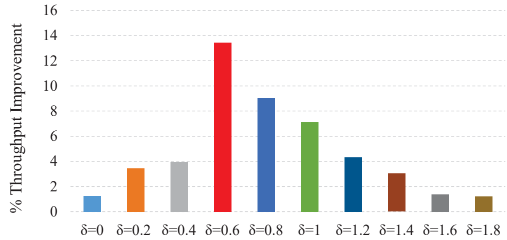
In this section, we explore the experimental evaluation of the performance of DSC algorithm when intelligent RTS/CTS control methods are used to mitigate the drawback associated with DSC. More specifically, we compare the IEEE 802.11 network that utilizes DSC algorithm along with intelligent RTS/CTS control mechanism with a network that utilizes only DSC network and with a legacy IEEE 802.11 based network. In the following sections, we demonstrate that the combined use of DSC along with 4-way handshake can be beneficial in terms of reduced overall FER and can even provide throughput and fairness gains.

A. *Evaluating methods to intelligent enable RTS/CTS*

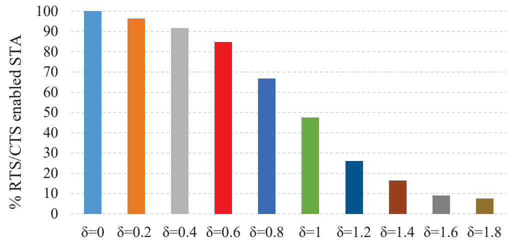
In this section, we evaluate the performance of methods proposed in Section II to intelligently select stations within a network for the RTS/CTS activation. The frame length used within the following analysis corresponded to the maximum allowed MAC Service Data Unit (MSDU) (i.e. 2302bytes) for IEEE 802.11.

1) Evaluating method 1: We start by first evaluating the implication of activating a percentage of RTS/CTS enabled DSC stations based on Method 1. Keeping in view the already proven improvements induced by the inclusion of DSC within densely deployed IEEE 802.11 networks, Figure 3a gives substance to the idea of intelligently utilizing RTS/CTS mechanism. Around 14% throughput improvement is witnessed when intelligent RTS/CTS plus DSC enabled network (utilizing δ of 0.6) is compared with only DSC enabled network. In terms of fairness, no notable difference was found between RTS/CTS plus DSC and DSC only networks.

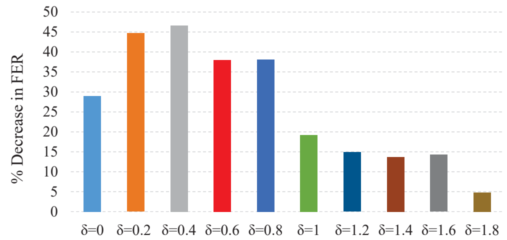
Figure 3c highlights considerable reduction in overall average FER of the network.



(a) Percentage increase of throughput.



(b) Percentage of RTS/CTS enabled nodes.

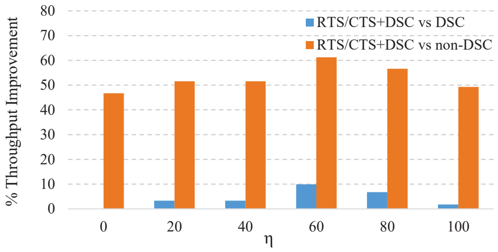


(c) Improvement in overall FER.

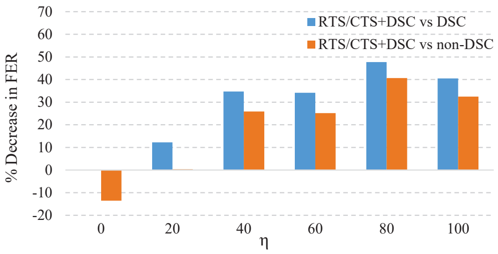
Fig. 3: Comparison of 4-way handshake enabled DSC stations utilizing method 1 with DSC-only stations.

2) Evaluating method 2: We implement the selection process in this section based on the Method 2 presented in Section II. The percentage of nodes utilizing RTS/CTS is gradually increased (i.e. 20, 40, 60, 80 and 100%). Figure 4a indicates considerable gains (i.e above 60%) achieved by only activating RTS/CTS on 60% of the stations when compared to a network that neither utilizes selective 4-way handshake, nor uses DSC (i.e. legacy IEEE 802.11 network). With respect to a network only employing DSC, this increase is around 10%. In addition, the fairness improved by 3% for RTS/CTS enabled DSC network. Figure 4b signifies the gradual improvements in FER, where around 48% decrease in FER is witnessed when 80% of DSC enabled stations utilize RTS/CTS (when compared to DSC-only scenario). Interestingly, FER improvement was also found when RTS/CTS enabled DSC network was compared with legacy IEEE 802.11 network, an indicator to the importance of intelligently enabling RTS/CTS.

In order to distinguish among the factors that lead to throughput improvements (i.e. whether the differences were

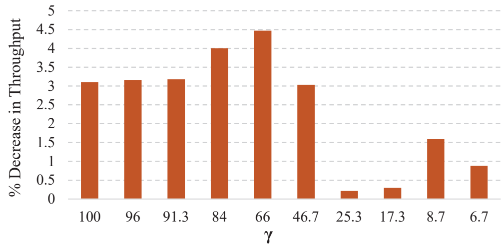


(a) Percentage increase of throughput.

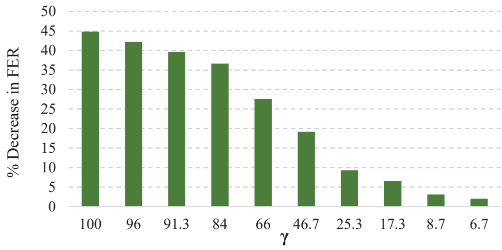


(b) Impact on FER.

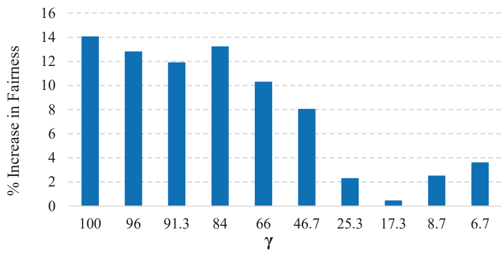
Fig. 4: Comparison of 4-way handshake enabled DSC stations utilizing method 2 with DSC only enabled stations and with a network that utilizes legacy IEEE 802.11 stations.



(a) Percentage decrease in throughput.



(b) Percentage decrease in FER.



(c) Improvement in overall Fairness.

Fig. 5: Comparison of 4-way handshake enabled DSC stations utilizing method 3 with only DSC enabled stations.

due to DSC with RTS/CTS or RTS/CTS only), we also analyzed the performance of using 4-way handshake on selected nodes without using DSC. When a network in which 60% of the non-AP stations within a cell utilized RTS/CTS was compared to a network that neither used 4-way handshake nor utilized DSC, only 10% throughput improvement was witnessed. Thus indicating the importance of utilizing DSC with selective RTS/CTS that complement to achieve better performance results (i.e. 60% throughput improvement).

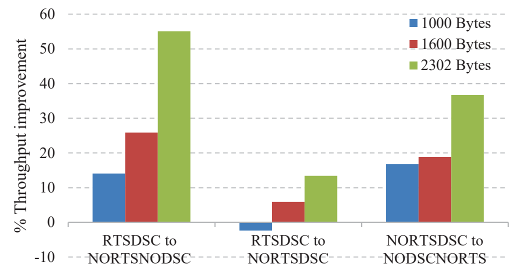
3) Evaluating method 3: In this section, we evaluate the performance of a network that intelligently varies the percentage of stations utilizing RTS/CTS based on the hidden node count. The rational to conduct this study was based on our understanding that DSC increased FER in the system due to the dynamic decrease in carrier sensing range that results in the increase of hidden count number.

In order to make the results more observant and to correlate with a FER based method evaluated in Section IV-A1, we choose the γ as the percentage of stations selected for RTS/CTS in Section II-A (i.e. we chose the same number of stations highlighted in Figure 3b by varying different δ values). Intuitively, the number of hidden nodes of a particular station and its measured FER would be correlated (more hidden nodes mean more collisions and thus a higher FER). In that case, the performance of Methods 1 and 3 should be similar; however, the results in Figure 5 show notable discrepancies (lower throughput and higher fairness). A large number of hidden nodes may result in a surprising low FER if those hidden nodes do not have many transmission opportunities.

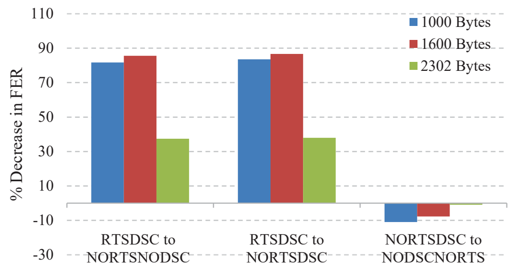
Based on the aforementioned analysis, we indicate that FER is a reliable metric for RTS/CTS selection and can increase the overall performance of a DSC enabled network. Furthermore, it is a general metric that is easy to calculate and can be measured in real environments that can include interference/noise as well as mobility.

B. *Impact of frame size on RTS/CTS enabled DSC stations*

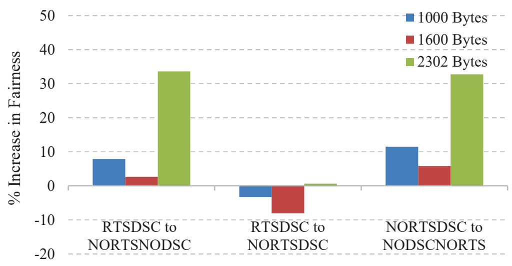
As highlighted in previous section, intelligent method to enable RTS/CTS control can have multifold benefits. In this section, we build on the proposed argument where different frame sizes are used (i.e. 1000, 1600 and 2302Bytes) for comparative evaluation of a dense WLAN network. In SectionIV-A1, we exposed maximum benefits when $\delta = 0.6$. We utilize the same δ and apply Method 1 so as to perform the following analysis: we compare the RTS/CTS enabled DSC nodes (RTSDSC) with a network encompassing RTS/CTS disabled DSC nodes (NORTSDSC) and a network that neither utilizes DSC nor uses 4-way handshake (NORTSNODSC). Figure 6a indicates approximately 55% improvement in throughput for the largest frame size. RTS/CTS control was found to add to the benefits of DSC for all cases. According to Figure 6b, maximum FER improvements were achieved for small frame size. In terms of fairness, RTSDSC provides substantial benefits when compared to NORTSNODSC network. An important outcome of the aforementioned results is that for large frame sizes, RTS/CTS can be beneficial. On the other hand, for small frames size, RTS/CTS method can be an overhead that can lead to system performance degradation, even in a dense environment, where the number of hidden nodes is large.



(a) Percentage increase of throughput.



(b) Impact on FER.



(c) Improvement in Fairness.

Fig. 6: Performance evaluation of RTS/CTS enabled DSC stations with varying frame sizes

V. Related Work

In order to resolve the hidden node problem associated with DCF, several researchers have envisioned the adaptive usage of RTS/CTS, where the aim has been to reduce the impact of collisions. Although the usage of RTS/CTS method can reserve the channel that can help in reduced frame collisions, the added overhead due to the inclusion of RTS and CTS transmission is not negligible [10] (especially at high data rate transmissions). The benefits associated with enabling and disabling the 4-way handshake has already been explored in numerous previous research works (e.g. [11], [12], etc.). Different researchers have proposed the usage of different metrics to enable RTS/CTS exchange (e.g. packet delivery ratio [13], hidden terminal count [14], successful transmitting probability of packets [15], etc.). Recently, authors in [16] have proposed to utilize RTS/CTS in Machine to Machine (M2M) scenario, where many RTS frames are sent in parallel by different stations on different frequency sub-bands. In such scenario, RTS frames will seldom collide and therefore major improvements in saturation throughput and delay for loaded networks were exposed by the authors. However, the drawback of this scheme is the need to have many sub-carriers to perform the aforementioned mechanism. To the best of our knowledge, no previous work explores the benefits of utilizing 4-way handshake in high density IEEE 802.11 networks.

VI. Conclusion

In this paper, we propose the intelligent utilization of AP controlled 4-way handshake uplink access to improve and enhance the performance of DSC enabled network, leveraging two of the mechanisms under the consideration of the TGax to enhance spatial reuse in future IEEE 802.11ax devices. Through extensive simulations we show how an intelligent selection of the set of stations using RTS/CTS access minimizes the negative effects of an adaptive CCA mechanism such as DSC. As a result of that combination, up to 60% throughput improvements are achieved while increasing fairness and reducing FER.

Acknowledgments

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