Dynamic Sensitivity Control of Access Points for IEEE 802.11ax

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Abstract—**The popularity and wider acceptance of IEEE 802.11 based WLANs has resulted in their dense deployments in diverse environments. While this massive deployment can potentially increase capacity and coverage, the current physical carrier sensing of IEEE 802.11 cannot limit the overall interference induced and also cannot insure high concurrency among transmissions. Recently, the IEEE 802.11 working group has continued efforts on developing WLAN technology through the creation of the TGax, which aims to improve efficiency of densely deployed IEEE 802.11 networks. In this paper, we propose a Dynamic Sensitivity Control for Access Point (DSC-AP) algorithm for IEEE 802.11ax. This algorithm dynamically adjusts the Carrier Sensing Threshold (CST) of an AP based on received signal strength from its associated stations and interfering APs. We show that the aggregate throughput of a dense network (under asymmetric traffic conditions) utilizing DSC (both at the stations and AP) is considerably improved (i.e. up to 32%) when compared with legacy IEEE 802.11.**

I. INTRODUCTION

The IEEE 802.11 WG has actively continued to release new draft amendments to incorporate latest technological advances to defy new practical challenges. As compared to the cellular technologies, IEEE 802.11 standards/amendments are released to be backwards compatible and thus pile atop of each other by adding and removing key technical aspects. Most recently, the IEEE standardization committee has approved IEEE 802.11ax Project. TGax is currently working on the extension of the IEEE 802.11ac standard, but this time aiming to improve the system capacity instead of increasing the supported data rates at link level. More specifically, this new project is intended to improve the efficiency in scenarios that are interference limited (due to high density of IEEE 802.11 devices). As mentioned in IEEE 802.11ax working document [1], one of the main objectives of the proposed amendment is to increase the spectral reuse and improve interference management in OBSS to achieve higher throughputs. The current IEEE 802.11 standard, when applied to dense scenarios, can result in limited spatial reuse because they utilize overprotected channel access methods.

In IEEE 802.11, Distributed Coordination Function (DCF) is the dominant/default carrier sensing mechanism to access the medium. DCF utilizes Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol that enforces nodes to contend to gain access of the shared medium resources. In order to detect the channel condition, Physical Carrier Sensing (PCS) is used within DCF where each node (intending to transmit) examines the status of the channel prior to transmission. If the measured energy level is above a predefined threshold (called Carrier Sensing Threshold (CST)), the node senses the channel to be busy and thus defers its transmission. A more aggressive (i.e. higher) CST will result in more transmission opportunities at the cost of increased collision probability. Thus, CST can be optimally tuned so as to increase efficiency within dense networks.

A. Related work

The implication of physical carrier sensing to reduce interference and to increase performance (due to improved spatial reuse) have been extensively investigated by different researchers [2]. In the legacy IEEE 802.11 standard [3], CST values for AP and non-AP stations are set conservatively to prevent concurrent transmissions within a large area, known as carrier sensing range, when multiple nearby transmitters could actually operate simultaneously without causing ample degradation in channel conditions. Therefore, the main optimization problem is to choose a CST value that would allow multiple simultaneous links to operate together and, as a consequence, increase the overall throughput and fairness of the network.

In [4], the authors analytically model the relation of CST with transmission power and data rate within high density WLAN networks. They propose to change the CST based on the Received Signal Strength Indication (RSSI) of received frames, yet they assume fixed total interference in their overall analysis that can be considered a drawback of their proposed scheme. In [5], the authors have also visualized the usage of RSSI to modify the CST of each non-AP station, but they require special signaling (called Busy/Idle signal) that is used to monitor the RSSI variations. Similarly, [6][7] investigate the increase in performance of IEEE 802.11 networks by optimally adjusting CST, but their proposed algorithm require additions to the standard that may lead to added complexity.

In [8], the authors have investigated a technique to improve network capacity in hotspots by dynamically tuning CST. They analyze an infrastructural Wi-Fi configuration where AP's CST is set according to the minimum measured Signal to Interference plus Noise Ratio (SINR) at the associated stations. Similarly, the CST of the stations is set based on the SINR of frames received at their respective APs. Albeit being one of few studies where carrier sensing is evaluated in the complete infrastructure WLAN dense network, this scheme introduces overheads due to the continuous sharing of SINR information among APs and stations.

Authors in [9] have highlighted the overhead involved in dynamic CST adaptation and proposed to use a camera to calculate the positions of nodes, which is in return used to calculate the CST for APs. Despite of the improvements indicated by the authors, their scheme itself creates an overhead in terms of added hardware.

Jamil et al. have evaluated the use of dynamic CST modification in [10][11], but they have not proposed algorithms.

Our previous research work in [12] includes the evaluation of an algorithm proposed in [13] (as a submission to the IEEE 802.11ax task group) for dynamically adjusting the CST (called Dynamic Sensitivity Control (DSC)) of non-AP stations. We described in detail the functionality of the algorithm and calculated the recommended parameters that provide maximum efficiency. We compared the algorithm with non-DSC network and exposed more than 20% improvement in throughput.

In this paper, we extend our previous work by first providing analytical justification for dynamically adopting CST threshold of each station (that constitutes the core methodology of DSC algorithms). Furthermore, we evaluate the impact of DSC (only at non-AP stations) in a network that contains uplink and downlink traffic. By doing so, we validate the need of introducing DSC algorithm at the APs as well. We then propose a DSC-AP algorithm that dynamically adjusts the CST of APs and expose an increase in throughput within a dense network while utilizing DSC at stations as well as APs. Importantly, we study the impact of DSC on system performance under asymmetric traffic that provides vital and comprehensive discussion of various aspects of the proposed scheme in more realistic environment.

The remainder of the paper is organized as follows. In Section II, we discuss the challenges of setting an optimal carrier sense and show that the power of the intended link (and the power of potential interferers) can be used as the basis of a distributed CST management scheme. In Section III, we emphasize the need to optimally adjust CST for all stations within WLAN network. In Section IV, the concept and implementation details of Dynamic Sensitivity Control Algorithm for access points are exposed. The details of simulation environment are given in section V. In section VI, the performance evaluation of DSC and DSC-AP in dense building environment is presented.

II. PROBLEMS ASSOCIATED WITH CARRIER SENSING IN DENSE NETWORK

Due to the inherent conservative approach of DCF in assessing interference, it is unable to efficiently access the shared medium. For example, if the Clear Channel Access (CCA) module (implemented at the physical layer) reports to the MAC layer that the medium is busy, the station blocks its own transmission so as to yield for other ongoing communication. However it may happen that the station unnecessarily blocked itself, since its transmission might not have caused enough interference to corrupt frames on an ongoing communication. This problem (referred to as exposed node problem) has been thoroughly investigated to severely affect the spatial reuse of spectral resources. On the other hand, if the CCA module reports the medium to be idle, the station can initiate its transmission where the SINR at the receiver determines whether the transmission was successful or not. However, in dense WLAN deployments, concurrent transmissions outside the carrier sensing range of a transmitting station can contribute to ample interference which, in return, can corrupt the ongoing communication. This problem (known as hidden node problem) causes collisions.

Both hidden and exposed node problems result in decreased overall throughput. Exposed node problem for a station occurs due to excessively small CST values where the transmitter detects faraway transmissions and, as a consequence, it unnecessarily defers its transmission. On the other hand, the cause of hidden node problem is the usage of a high CST at the transmitter, where energy received from a node (hidden) is lower than the CST. Having a conservative approach of assigning CST in the network can cause more exposed nodes to occur that can lead to unnecessary starvation. In the following section, we use a simple approach to show how CST can be derived to maximize spatial reuse in a dense environment.

A. Communication model to obtain appropriate CST

According to the simplified two-ray path-loss model (with antenna heights of 1m and gains of 1dB), the power a station receives from the transmitting node should be above a given threshold (called receiver sensitivity) for it to be correctly decoded and can be represented by,

$$P_r = \frac{P_t}{d^\alpha} \geq S_r \tag{1}$$

where, α is the pathloss exponent and its normal value for indoor communication is assumed to be in the range of 2 to 4. P_t and S_r are the transmitted power and the receiver sensitivity respectively.

For the sake of simplicity, let us assume that all stations are equal (i.e. same P_t, S_r, etc.). Using equation (1), the transmission range (i.e the region around the transmitter where the received signal strength from the transmitter is greater than or equal to the receiver's sensitivity) can be given as,

$$T_R = (\frac{P_t}{S_r})^{\frac{1}{\alpha}} \tag{2}$$

In order to determine whether the channel is free or busy due to a nearby transmission, the CCA method defines the carrier sensing range (i.e the region around the transmitter where the received signal strength is greater than the CST). Within this range, nodes are able to sense signals over the shared medium, even though the correct reception of packets may still not be possible. The carrier sensing range can be represented as,

$$CS_R = (\frac{P_t}{CST})^{\frac{1}{\alpha}} \tag{3}$$

In order to derive the interference range (i.e the region around a receiver in which any two simultaneous transmissions may result in a collision), we consider the scenario presented in Figure 1 where we assume that a node *A* transmits a packet to node *B*, but *B*'s strongest interferer, node *C* (that is hidden from node *A*), starts another transmission at the same time (power received by *B* from *A* is $P_{AB} = P_t/d_{AB}^\alpha$, where d_{AB} is the distance between *A* and *B*. Similarly, the power received by *B* from *C* is $P_{CB} = P_t/d_{CB}^\alpha$. The two signals can overlap in time, but the receiver could be able to decode one of the received packets (let's say from *A*) due to the *capture effect* (i.e. upon collision, packet with strongest signal will be successfully received, while the weaker signal will have the same effect as noise). This effect is observed when the Signal to Interference Ratio (SIR) of the received packet is greater than a given threshold (called Capture Threshold, C_t). According to [14], this threshold depends, fundamentally, on the hardware characteristics and the configuration of the PHY layer (i.e. C_t increases with PHY rate). Ignoring thermal noise

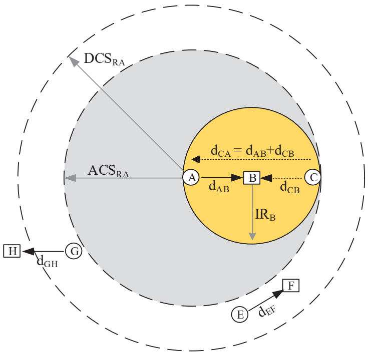

Fig. 1: Appropriate carrier sensing range that just covers the interference range.

and assuming all transmitters use same transmit power, we have,

$$SIR = \frac{P_{AB}}{P_{CB}} \geq C_t \implies (\frac{d_{CB}}{d_{AB}})^{\alpha} \geq C_t \tag{4}$$

This equation implies that, in order to successfully receive a signal from *A*, the interfering node *C* must be, at least, $C_t^{\frac{1}{\alpha}} \times d_{AB}$ meters away from the receiver *B*. In the limit:

$$d_{CB} = C_t^{\frac{1}{\alpha}} \times d_{AB} \tag{5}$$

The transmission range of a node is generally considered to be much smaller than the carrier sensing or interference range. The receiver sensitivity (defining the transmission range) and capture threshold depend on the characteristics of the hardware, whereas the carrier sensing range is tunable (through CST adaptation) and can greatly affect the performance of the network. Being $d_{CA} \leq d_{AB} + d_{CB}$[1], setting

$$CS_{RA} = d_{AB} + d_{CB} \tag{6}$$

the carrier sensing range of *A* covers *B*'s interference range (presented as IR_B in Figure 1); that is, any transmission outside CS_{RA} will not cause a collision in *B* and could thus be safely ignored when *A* senses the medium before transmitting to *B*, avoiding exposed nodes (e.g. nodes *E* and *G*). Hence, to compute the proper CST for *A*, we first compute the minimum power *A* receives from *C*,

$$P_{CA} \geq \frac{P_t}{(d_{AB} + d_{CB})^{\alpha}} \tag{7}$$

Combining equations (5), (7) and using $P_{AB} = P_t/d^{\alpha}_{AB}$, we have,

$$P_{CA} \geq \frac{P_{AB}}{(C_t^{\frac{1}{\alpha}} + 1)^{\alpha}} \tag{8}$$

Finally, the *A*'s CST that allows an increased spatial reuse and, at the same time, prevents collisions with *C* is given by

$$CST_A = \frac{P_{AB}}{(C_t^{\frac{1}{\alpha}} + 1)^{\alpha}} \approx \frac{P_{BA}}{(C_t^{\frac{1}{\alpha}} + 1)^{\alpha}} \tag{9}$$

where, $P_{BA} = P_t/d^{\alpha}_{BA}$, where$P_{BA} \approx P_{AB}$ due to assumed similar transmit power P_t.

This improved CST value is represented by ACS_{RA} in Figure 1. To justify this argument, we consider a typical domestic scenario where we assume that the power received at a node from its transmitter (within a cell) is -55dBm and C_t is set to be 15dB [14]. Furthermore, if we assume $\alpha = 3.5$ (which corresponds to the value used by the IEEE 802.11 TGax to develop the path loss model [15]) and substitute these values in equation (9) , the CST obtained is ∼-75dBm, which is greater than the default CST (i.e. -82dBm) used by the current IEEE 802.11 standard (represented by the DCS_{RA} radius in Figure 1). Consequently, it would decrease the carrier sensing range of the node and thus will allow more concurrent transmissions to take place around that transmitter. Correspondingly, we justify our observation that the power received from the intended receivers can be used as a viable and simple solution for a node to set its CST. In section IV, we infer the aforementioned concept to design an algorithm that enables APs to set their CST to optimal values based on the power received from their associated stations.

III. NEED TO DYNAMICALLY ADJUST CST OF STATIONS AS WELL AS AP WITHIN DENSE WLAN DEPLOYMENT

In our previous work [12], we evaluated a method to dynamically adjust the CST of stations in an environment where only uplink transmission was used in saturation condition. All the transmitters (i.e. non-AP stations) adjusted their individual CST based on the power of beacons received from their respective APs. Despite of improvements in overall throughput, this scheme cannot provide maximum benefits when both uplink and downlink transmission occur. This is due to the fact that, in such environments, APs (that also add to the set of transmitters) can also contribute or get affected by starvation caused by exposed node problem.

In order to exemplify the aforementioned argument, we utilize Figures 2 and 3 to signify the extent of hidden and exposed node problem within densely deployed un-managed WLAN networks. The aforementioned figures are graphical representations of five rooms of a particular floor (out of one hunderd rooms) within a densely deployed WLAN residential simulation environment (Section V highlights the details of the environment), with two-way communication (uplink plus downlink). Hidden and exposed node analysis is performed by measuring the received power at each station from every other station, and comparing it with the corresponding CST. We consider two nodes X, Y to be hidden from each other if they are not within each other's CS_R (P_{XY} < CST_Y and P_{YX} < CST_X) and a station Z, which is the intended receiver of either X or Y, is placed within both X's and Y's transmission range (P_{XZ} > Sr_Z and P_{YZ} > Sr_Z). Conversely, nodes X and Y are exposed if they are able to defer each other's transmissions but are unable to reach each other's receivers. Figure 2 depicts the case where the entire transmitter set utilizes similar CST (-82dBm). All the nodes are found to have, at least, one hidden pair, and 33% of the stations are found to be exposed to other transmitters.

In Figure 3, our proposed CST adaptation (i.e. DSC) is applied only at non-AP stations. Results highlight that there is significant reduction in exposed nodes count (i.e. from 33% to 13%) when compared to the environment where all transmitter use the same CST value. As a consequence, the number of nodes that are hidden from six or more stations is increased (i.e from 57% to 66%). More specifically, the number of exposed non-AP stations decreased from 28% to 4% due to DSC being

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[1] In Figure 1, transmitters A and C are aligned that result in maximum separation distance of $d_{CA} = d_{AB} + d_{CB}$. However, for a more generic case, the separation can be $d_{CA} < d_{AB} + d_{CB}$.

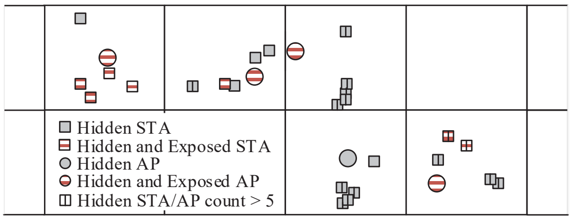

Fig. 2: Default CST used by all the transmitters.

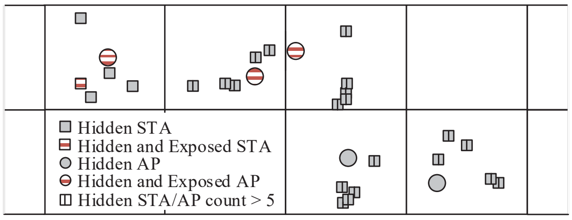

Fig. 3: DSC applied at non-AP stations.

employed only at the uplink. On the contrary, most of the APs still suffer from exposed nodes, thus justifying the need to have a method that modifies CST at the APs as well. Furthermore, as a consequence of the mobility of stations and changes in the network scenario, received power varies over time, and hence CST tuning should be continuous and dynamic.

As a solution to reduce the impact of increase in hidden node count (that results in increased in frame error rate), a conventional interference management scheme (i.e. RTS/CTS) can be used. However, the combination of RTS/CTS and DSC is out of the scope of this work.

IV. Dynamic Sensitivity Control Algorithm for Access points (DSC-AP)

The basic idea of DSC schemes (for all kind of stations, AP and non-AP) is to optimize the existing deployments by appropriately tuning CST for each node in a distributed manner (in order to avoid signaling overhead). In DSC scheme for non-AP stations [12], the CST of each non-AP station was varied based on the RSSI of beacon frames received from the associated AP. The DSC-AP scheme we propose operates to facilitate more concurrent transmissions to occur by tuning the CST of AP based on the RSSI received from its furthest associated station[2]. Therefore, the AP is able to confine/reduce its carrier sensing range to include only the links that operate within the cell (i.e. AP is able to serve the needs of all of its stations). In order to cater for a situation where an active interferer is nearest to the AP (as compared to associated stations), only then the CST of AP is tuned according to the interferer. In order to avoid excessive fluctuations of the CST and given that, typically, most of the traffic in a WLAN is originated from the AP, the algorithm only considers interference coming from neighboring APs. Thus, the underlying difference between the DSC for non-AP and the DSC-AP is that the latter keeps track of the furthest receiver and also considers RSSI information from dominant interferers.

In order to understand the basic operation of our DSC-AP, a flow chart is presented in Figure 4. We consider an infrastructure-based dense WLAN scenario where each station is already associated to its respective AP and the DSC algorithm is executed concurently over all the APs.

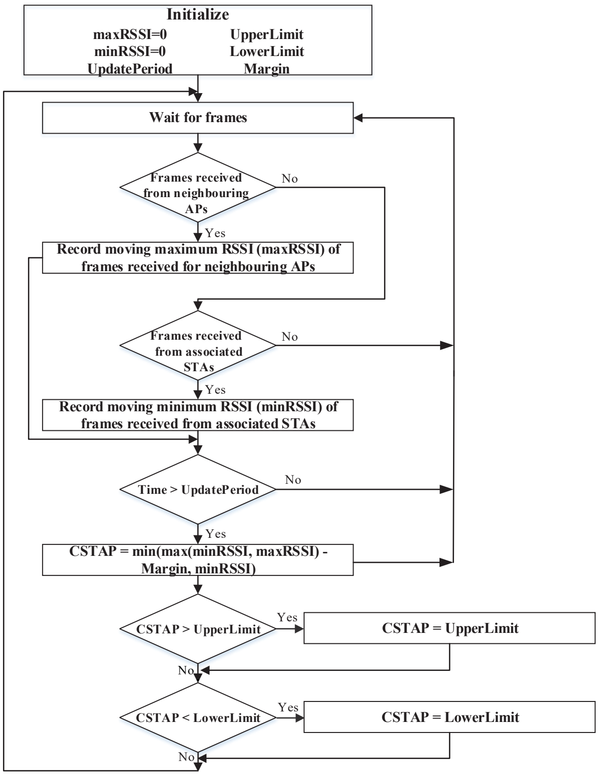

Fig. 4: Flow chart of DSC-AP algorithm used at each AP.

Furthermore, we consider two way communications where the AP keeps track of different frames (i.e. data, ACK, etc) received from its associated stations as well as from neighboring APs. Whenever the AP receives frames (that it is able to decode properly) from neighboring interfering APs or from its associated station, it records the RSSI of the frames up till the $UpdatePeriod$. This $UpdatePeriod$ time is a preset value that encompasses multiple Beacon Intervals (BI). The AP maintains a moving maximum RSSI (called $maxRSSI$) of the frames received from neighboring APs. By doing so, the AP is able to detect the closest interfering AP. For its own stations, the AP maintains a moving minimum RSSI (called $minRSSI$) of the frames received and thus is able to identify a station that is placed at a maximum distance from the AP.

If no frame is received from any stations within an $UpdatePeriod$, or if no frames are received from associated stations , the AP does not change its CST (even though frames are received from the neighboring interfering APs).

After every $UpdatePeriod$, AP tunes its CST. In the first step, the AP evaluates the maximum between $minRSSI$ and $maxRSSI$. Then Margin is subtracted from the previous calculated value and is used to set the CST of the AP. Margin value is kept constant for all the nodes and would correspond to $(C_t^{\frac{1}{\alpha}}+1)^{\alpha}$, depending on the modulation used and following equation (9)[3], as explained in Section II. However, as detailed in section VI-A, using a more realistic propagation loss model, this Margin value should be fine-tuned. In the next step, the new calculated CST is confined between an upper limit

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[2] A single appropriate CST for AP is calculated within a cell so as to avoid the complexity introduced by assigning different CSTs for transmissions to different associated stations.

[3] Margin values range between 18 and 25dB in typical indoor scenarios (i.e. $\alpha \sim 3.5$).

($UpperLimit$) and lower limit ($LowerLimit$) so that if the AP is located near its associated stations or neighboring AP, it is assigned a CST that falls near the upper limit and vice versa.

In the flowgraph, the decision to consider the maximum between the $minRSSI$ and $maxRSSI$ is based on fact that in a residential scenario, stations are always placed near to their respective APs and the AP should prefer its own stations to set its CST.

The above mentioned DSC-AP algorithm effectively allows more flows to coexist and, as shown in section VI, results in higher per flow and aggregate throughput.

V. SIMULATION SETUP

In order to showcase the benefits of introducing DSC within dense WLAN deployments, we present a simulation-based study to evaluate the performance of IEEE 802.11 infrastructure network operated within dense building apartments. We compare the performance when DSC (at both stations and AP) was used against the legacy IEEE 802.11, in which a constant/default CST threshold was used in every node.

In our simulations, we considered the scenario defined by the IEEE 802.11ax WG in [15] consisting of a multi-floor residential building (see Figure 5) with the following specifications:

- 5 floors, 3m height of each floor
- 2×10 apartments in each floor
- Apartment size: 10m×10m×3m
- Building type: Residential
- External wall type: Concrete with windows

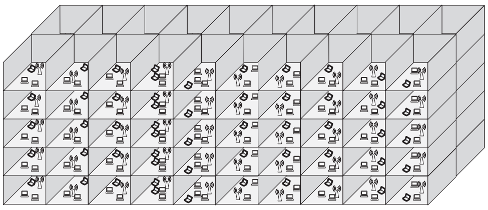

Fig. 5: Layout of dense deployment of IEEE 802.11 infrastructural network in residential building.

A single AP was randomly placed within the walls of each apartment. Five non-AP stations were placed around each AP randomly. Furthermore, APs selected channel 1, 6 and 11 at random so that each channel was shared by 1/3 of the cells. 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[4] was used. 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. To make our evaluation more realistic, we consider asymmetric traffic where uplink transmission rate is set to one-fifth of downlink transmission rate. Furthermore, we assume that saturation condition[5] (i.e. stations always have frames to transmit) is established within each cell. 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. We modified the NS-3 simulation package, a) to allow non-AP stations to measure the received energy level of each beacon frame received from the relevant AP, b) to measure the received energy level of any frames by the AP, received from its associated stations as well as from its neighbouring APs, c) by improving hybrid building pathloss model to accommodate for floor penetration losses.

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[6] (calculated according to Jain fairness index); 4) number of hidden nodes; 5) number of exposed nodes. For the hidden node analysis, we considered a pair of hidden nodes (i.e. two nodes that are hidden from each other) as a single entry. This simplification was also used for the exposed node count. The description of Physical and MAC layer parameters used in our simulations 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 bytes
Frequency band	2.4 GHz	Trasmission power of STA and AP	16 dBm
Physical transmission rate	72.2 Mbps	Antenna gain	1 dB
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	20MHzt	Beacon Interval	100ms
Aggregation	not used	RTS/CTS	disabled

DSC algorithm for stations is optimized according to our findings in [12]. Furthermore, in both DSC algorithm (at the AP and station) $UpperLimit$ is set to $-40dBm$ and $LowerLimit$ is set to $-82dBm$. Also, $2s$ of $UpdatePeriod$ is used within these algorithms.

VI. SIMULATION RESULTS AND DISCUSSION

In this section, we evaluate the performance of the proposed DSC-AP algorithm through an extensive simulation study. In the following sections, we demonstrate that DSC-AP algorithm provides multifold benefits in dense IEEE 802.11 implementations.

A. Recommended parameters for DSC-AP algorithm

We first evaluate DSC-AP algorithm to uncover the recommended value for $Margin$ which provides maximum efficiency in the simulation environment under consideration.

In Section II-A, we derived an analytical model to set CST of a node based on received power from its intended transmitter/transmitters. In order to justify our analysis, we demonstrated a simple example where the CST value was set to be approximately 20dB less than the received power (the difference between the received power of -55dBm and

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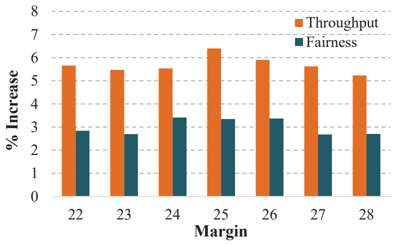
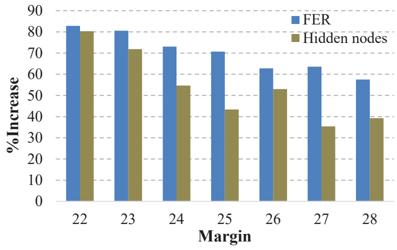
[4] Hybrid Buildings Propagation Loss Model: NS3-Design document: http://www.nsnam.org/docs/models/html/buildings-design.html.

[5] Saturation is used to explore maximum capacity.

[6] Overall fairness in the network is calculated based on per flow analysis.



(a) Throughput and Fairness improvements with DSC-AP.



(b) Increase in FER and number of hidden nodes with DSC-AP.

Fig. 6: Increase of different metrics when DSC-AP is in used for different $Margin$ values.

the newly calculated CST of -75dBm). This value can be considered as a benchmark around which the optimal value can be selected (fine tuned) for more realistic environments. This optimal value, when added to the received power, could result in optimal CST selection of a node and thus results in increased spatial reuse.

In this section, we consider a network encompassing only downlink traffic in which all AP stations implement DSC-AP and utilize a fixed offered load (i.e. 6Mbps that lead to saturation condition) over every AP to station link. Figure 6a presents the percentage increase in aggregate throughput and fairness for all the APs while utilizing different $Margin$ values. The throughput results indicate around 6 % improvements for all the cases over the conventional IEEE 802.11 protocol. The proposed algorithm increases the aggregate throughput along with fairness in the system. Maximum fairness benefits are achieved when $Margin$ values of 24, 25 and 26 are used.

Figure 6b highlights the increase in FER and hidden nodes while utilizing DSC-AP. Higher $Margin$ values caused less hidden nodes. Another important outcome is that the presence of exposed nodes is driven to 0.

As a consequence of the increased number of hidden nodes, the overall FER in the network is also increased. However, the impact of an increased FER can be reduced by the MAC level stop-and-wait ARQ used in 802.11 transmissions. It is important to mention that higher values of $Margin$ induce smaller FER degradation. This is due to the fact that the impact of $Margin$ results in lower i.e. more conservative CST of APs and thus the carrier sensing range is increased. As a consequence, the FER is decreased due to less hidden nodes.

Comparing Figures 6a and 6b, it is pertinent to mention that the DSC-AP scheme provides improvements in throughput and fairness at the cost of increasing FER and hidden nodes. After closely analyzing the results, we chose $Margin$ of 25 to be the recommended parameter that creates a balance between the negative and positive aspects of DSC-AP. We employ this value for DSC-AP algorithm in the remainder of the paper.

B. Dynamic vs. static CST adaptation

In order to demonstrate the benefits of dynamically adjusting CST of the APs, in this section we compare the performance of DSC-AP with a scenario where constant increased CST (i.e. -70dBm) is assigned to all APs. Downlink transmission in saturation conditions is utilized for the new set of simulations, where a percentage improvement of DSC-AP and fixed CST with respect to APs utilizing default CST (i.e -80dBm) is considered. The performance comparison is represented in Figure 7. DSC-AP algorithm is found to increase throughput along with fairness with reduced percentage increase in hidden nodes. Despite of improvements witnessed due to increased spatial reuse, fixed CST scheme was only found to perform better than DSC-AP in terms of FER. Both of the schemes were found to eliminate the presence of exposed nodes.

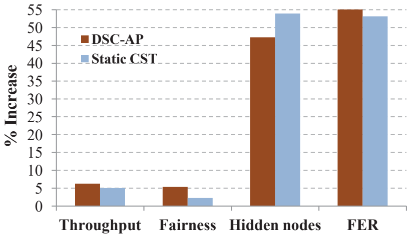


Fig. 7: Percentage increase in different metrics for DSC-AP and static CST.

C. Evaluation of DSC and DSC-AP algorithm in asymmetric traffic

In this section, we expose the performance of a network (employing asymmetric traffic) where DSC-AP at downlink is used in combination with DSC at the uplink. The overall performance is compared to the network where default CST is utilized by each node.

Figure 8 shows approximately 7% throughput improvement for DSC network over conventional IEEE 802.11 protocol. Furthermore, it was witnessed within the simulations that, due to asymmetric traffic, major throughput benefits were achieved at APs due to DSC-AP (as compared to DSC algorithm at stations). Recall that APs carry most of the traffic. Moreover, DSC algorithms were found to improve the overall fairness in the network.

As a consequence of the increased number of hidden nodes, the overall FER in the network increased (from 0.14 to 0.18) due to an increased collision probability. These results are also presented in Figure 8. Even though the overall FER

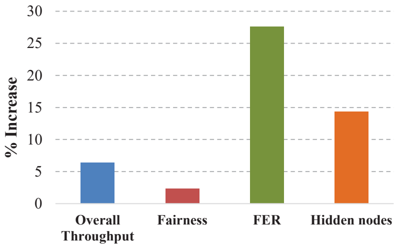


Fig. 8: Percentage increase in different metrics when DSC is used at each station.

is increased, the proposed DSC-AP algorithm helps greatly in improving the overall throughput of the network.

D. Combining DSC with Channel Selection

Figure 9 shows the performance of DSC (at AP and non-AP stations) under optimal channel selection[7](so as to avoid/minimize interference between neighboring co-channel cells and thereby maximise network capacity). As mentioned in [16], the DSC algorithm can be combined with an intelligent channel selection to provide increased efficiency.

We simulate IEEE 802.11n network with OPtimal CHannel Selection with DSC (OPCH+DSC) and compare its performance with the following scenarios, a)IEEE 802.11n network with OPtimal CHannel Selection without DSC (OPCH+NODSC) b) IEEE 802.11n network using Random CHannel Selection with DSC (RCH+DSC), c) IEEE 802.11n network with Random CHannel Selection without DSC (RCH+NODSC) .

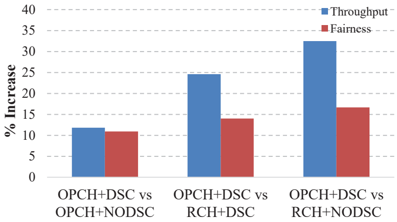


Fig. 9: Comparison of OPCH+DSC scheme in terms of % increase of throughput and fairness.

1) Throughput comparison: It is worth noting that the scenarios where DSC is combined with optimal channel selection provide maximum throughput gains of more than 30% when compared with a network that utilizes neither DSC nor channel selection. Additionally, approximately 25% improvement was witnessed when DSC network utilizing optimal channel selection scheme was compared with a DSC enabled network that did not utilize optimal channel selection . Individually, as seen in Figure 8, DSC improved throughput by approximately 7% whereas, on a network with an optimized frequency management only , DSC was able to increase it up to 12%. This result validates the aformentioned argument that DSC provides increased efficiency when utilized in optimal channel selection environment.

2) Fairness analysis: It is logical to think that DSC may decrease fairness by giving more transmission opportunities to nodes that are near the AP, since they set higher CST values. On the other hand, DSC reduces the number of exposed nodes, which may become starved when they are located between two unsynchronized transmitters. Figure 9 indicates that fairness is considerably increased in all the scenarios when DSC is used. This validates our previous conclusion that DSC increases the aggregate throughput by fairly increasing throughput over all the nodes.

VII. CONCLUSION AND FUTURE WORK

This paper introduces a DSC-AP scheme for IEEE 802.11ax that increases spatial reuse and limits the effects of an increased interference at an AP within dense deployments. The proposed scheme dynamically tunes CST of an AP based on the received signal strength from its associated stations and surrounding APs. We first derive a simple estimate of the appropriate CST in dense deployments. Then, we argue the need for DSC-AP and detail the functionality of DSC-AP algorithm. Furthermore, we utilize NS-3 simulator to evaluate the benefits provided by DSC-AP, as compared to the legacy IEEE 802.11. Detailed simulation results indicate that DSC (both at the AP and stations) allowed multiple concurrent transmissions to coexist, thus increasing the overall throughput over the cost of increased hidden nodes and FER. Note, however, that the throughput improvements achieved in the current research work are bounded by the frame size; we expect more notable improvements by utilizing frame aggregation (the intention for our current work was to understand the benefits of introducing DSC schemes in a pure CSMA based network). Directions of future work include the study of RTS/CTS to overcome DSC drawbacks (increased hidden node problem).

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[7] In optimal channel selection, channels are selected at each AP so that the distance between co-channel cells is maximized.