Evaluation of the DSC algorithm and the BSS Color scheme in dense cellular-like IEEE 802.11ax deployments

Ioannis Selinis[1], Marcin Filo[1], Seiamak Vahid[1], Jonathan Rodriguez[2] and Rahim Tafazolli[1]

[1]Institute for Communication Systems 5GIC, University of Surrey
[1]{ioannis.selinis, m.filo, s.vahid, r.tafazolli}@surrey.ac.uk
[2]Instituto de Telecomunicacoes, Aveiro, Portugal
[2]jonathan@av.it.pt

***Abstract*—Coping with the extreme growth of the number of users is one of the main challenges for the future IEEE 802.11 networks. The high interference level, along with the conventional standardized carrier sensing approaches, will degrade the network performance. To tackle these challenges, the Dynamic Sensitivity Control (DSC) and the BSS Color scheme are considered in IEEE 802.11ax and IEEE 802.11ah, respectively. The main purpose of these schemes is to enhance the network throughput and improve the spectrum efficiency in dense networks. In this paper, we evaluate the DSC and the BSS Color scheme along with the PARTIAL-AID (PAID) feature introduced in IEEE 802.11ac, in terms of throughput and fairness. We also, exploit the performance when the aforementioned techniques are combined. The simulations show a significant gain in total throughput when these techniques are applied.**

***Index Terms*—WLAN, WiFi, IEEE 802.11ax, Physical Carrier Sensing (PCS), Dynamic Sensitivity Control (DCS), BSS Color, PARTIAL-AID (PAID)**

I. Introduction

During the past years, the number of portable devices that are connected to the internet has rapidly grown leading to more dense wireless local area network (WLAN) deployments. The global mobile data traffic increased by 69% during the last year, and it is expected to rise even more with the growth of the fourth-generation (4G) networks [1]. To meet the demands for high data rates and low latency a big share of that traffic will be offloaded on to Wi-Fi. It is a cost-efficient solution, whilst can boost the network capacity by 300% [2].

The interference levels in dense WLAN deployments are expected to increase, thus severely affecting the network performance. The authors in [3] study and present an interference analysis in dense networks. They argue that due to densification, the number of packet collisions, interference from neighbouring Basic Service Sets (BSSs), and the hidden/exposed node problem significantly degrade the network performance.

To address these demands in a wireless network, a new IEEE study group [4] started its activity in May 2014. The 802.11ax task group aims at improving the spectrum efficiency and the network throughput in dense network deployments with hundreds of Access Points (AP) and Stations (STA). The new features proposed in TGax are: 1024 QAM (as an optional modulation scheme), DL and UL OFDMA, DL and UL MU-MIMO (DL MU-MIMO is supported in 802.11ac), and the spatial reuse techniques such as the Dynamic Sensitivity Control (DSC) [8] and the BSS Color scheme [9] that this work presents and focus on.

There are several approaches that have been proposed in the literature in order to enhance the network throughput by improving the spatial reuse. The main two techniques proposed are the transmit power control (TPC) and tuning the physical carrier sensing (PCS) threshold. TPC is essential for decreasing the energy consumption in a station and reducing the interference level to the neighbouring nodes. However, it requires a sufficient number of power transmit levels [5], and coordination among the users, otherwise the SINR at the receiver could be extremely low, leading to outrages. Furthermore, the maximum transmit power is constrained by the regulatory bodies e.g. Federal Communications Commission (FCC). A PCS scheme could also be an effective way to enhance the spatial reuse in a network, whilst it does not require any modifications to the hardware or the IEEE 802.11 standard.

Even though there is a considerable amount of work in the literature (e.g. [6], [7]), performance of PCS in dense networks, has not been adequately evaluated, in the past. The DSC and the BSS Color scheme are the two main schemes under consideration by the 802.11ax working group, for improving spectral reuse, due to the potential gains they can provide. To the best of our knowledge, the performance of these schemes in such dense deployments along with the PARTIAL- Association Identifier (PAID), [10], feature of 802.11ac, have not been yet fully evaluated in the literature.

This work presents an evaluation of the aforementioned schemes in a high density wireless network, using NS3 simulation tool [11] assuming multi-cell deployment scenarios, identified in IEEE 802.11ax standard [12]. Furthermore, we present the performance when the aforementioned schemes are combined.

978-1-5090-3254-9/16/$31.00 ©2016 IEEE

The rest of the paper is organized as follows. Section 2, addresses the recent spatial reuse approaches that have been proposed. Section 3, describes the DSC algorithm, the PAID feature, and the BSS color scheme, while Section 4 presents the simulation scenario. Section 5 analyses the simulation results and Section 6 concludes this paper.

II. RELATED WORK

The carrier sensing mechanism in IEEE 802.11, supports two schemes; the mandatory PCS, and the optional virtual carrier sensing (VCS), which sets the network allocation vector (NAV) on the MAC layer, based on the RTS/CTS frames. The former scheme, which is also known as Clear Channel Assessment (*CCA*), determines whether the medium is *IDLE* or *BUSY*. *CCA* monitors the channel for preambles, and returns *BUSY* when the received energy from the concurrent transmissions is above a certain threshold (CCA/CS_{th}), and can be expressed as:

$$\sum_{n=1}^{k} Pr^{n,i} \geq CCA/CS_{th}^{i} \tag{1}$$

where k is the number of the total interferers to the node i, and $Pr^{n,i}$ is the received power from the transmitter n to the node i. The received power at a distance d, assuming that the ratio of the antenna gain to the antenna loss is equal to 1, in both the transmitter and receiver, and if we only consider the signal attenuation due to path loss, then the received power is:

$$Pr = \frac{Pt}{d^{\alpha}} \tag{2}$$

where α is the path loss exponent (typical values 2-4), and Pt the transmit power of the transmitter. We assume that the transmission power is the same for all nodes. The carrier sensing range is the minimum distance that allows two concurrent transmissions and occurs when $Pr = CCA/CS_{th}$. Specifically, from equation (2), the carrier sensing range can be expressed as:

$$CCA/CS_{range} = \left(\frac{Pt}{CCA/CS_{th}}\right)^{\frac{1}{\alpha}} \tag{3}$$

However, in a dense network due to the accumulative interference, the CCA/CS_{range} must be equal to the distance between the intended transmitter (i) and its furthest interferer node (r_i), in order for the node i to initiate a transmission. Let $A = \{Pr^{n,i}\}_{n=1}^{k}$ be the set of the received powers from the interferers of the node i. Assuming that α is the same for all nodes, and each of them experiences the same channel conditions, the minimum received power corresponds to the furthest interferer node. If equation (1) holds, we then determine the CCA/CS_{th}^{i} as:

$$CCA/CS_{range}^{i} = \left(\frac{Pt}{\min A}\right)^{\frac{1}{\alpha}} \tag{4}$$

A node can decode the received signal, if the received signal level is above a threshold named receiver sensitivity (or Signal Detection) (CCA/SD_{th}). The maximum transmission range, from equation (2) can be calculated as:

$$CCA/SD_{range} = \left(\frac{Pt}{CCA/SD_{th}}\right)^{\frac{1}{\alpha}} \tag{5}$$

That is, the higher the CCA/CS_{th} is, the smaller the CCA/CS_{range} is, and the nodes are more aggressive in accessing the medium. An extremely low CCA/CS_{th}, increases the number of exposed nodes in a network. On the other hand, a very high threshold increases the number of hidden nodes. It has been shown that these nodes severely affect the spatial reuse [13], reducing the network capacity. The authors in [14], [15] show that the optimal CCA/CS_{th}, which maximizes the network throughput, allows a certain number of hidden end exposed nodes to exist. Furthermore, they argue that there is a balance between these nodes and the capacity which can be achieved by using a PCS mechanism.

The authors in [16] introduce the K-APCS algorithm that incorporates 802.11k radio resource management to obtain the metrics needed to tune the CCA/CS_{th}. The CDPCS algorithm presented in [17], adjusts the CCA/CS_{th} based on the area that a particular node is. It requires the use of the RTS/CTS frames to define the area. Both algorithms, introduce overheads in order to tune the CCA/CS_{th}.

The authors in [18], propose a decentralized approach for setting the CCA/CS_{th}, based on the beacon's Received Signal Strength Indication (RSSI), similar to the DSC scheme. However, DSC differs from the algorithm in [18], as it uses a moving average to compute the threshold, and it also decrements it after *X* consecutive missed beacons. The authors in [19] evaluate the DSC scheme in a multi-floor residential building, considering only uplink transmissions, and tuning only the CCA/CS_{th}.

The authors in [20] study the performance of the DSC and the BSS Color scheme for uplink transmissions. The same authors in [21] evaluate the performance of the BSS Color scheme if a 2^{nd} threshold is used when color mismatched occurs. In both cases, DSC outperforms over the BSS Color technique, however they argue that the throughput gain increases when these two techniques are combined. However, they consider a 19-cell deployment with spatial reuse factor 3 in their simulations. They do not consider the wrap-around scheme, which can potentially lead in overestimating the network performance. On the contrary, we evaluate both schemes in a high density deployment with spatial reuse factor 1 (with wrap-around) for both uplink and downlink transmissions. We also, evaluate joint tuning of the CCA/CS_{th} and the CCA/SD_{th} and also its combination with the Color scheme.

III. DESCRIPTION OF THE SCHEMES

In this section, we provide an overview of the DSC algorithm, the PAID feature, and the BSS Color scheme. The DSC algorithm, tunes the carrier sensing range and the transmission range in every STA, locally. In particular, it does not require any information from the neighbouring STAs, thus it does not introduce any overhead. The main idea derives from the fact

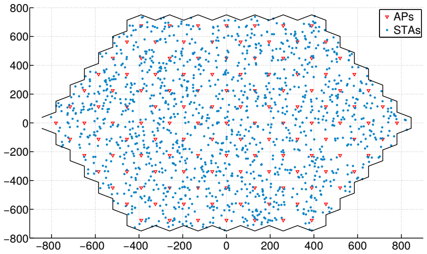


Fig. 1: Simulated scenario (approximately 1.85 km^2).

that stations at the edge of a cell should use lower CCA/CS_{th} than those placed close to their associated AP. This is because the edge-cell nodes should increase their sensing range to eliminate the hidden nodes, increasing the probability of correct transmissions. On the other hand, the stations that are placed close to the AP, have higher probability of a successful transmission due to their short distance to the AP. The DSC algorithm sets an *UpperLimit* that corresponds to the maximum CCA/CS_{th} (or CCA/SD_{th}) that a node can have, to prevent the stations placed close to an AP to gain access more often than the others. It also sets a decrement value by which the threshold decreases, after *X* consecutive missed beacons. DSC records the beacons' RSSI and calculates the thresholds using a moving average over the last *x* RSSI recorded values, according to $CCA/CS_{th} = \overline{RSSI} - Margin$. A similar procedure is followed for the CCA/SD_{th}. The value of the *Margin* must be carefully selected. In particular, an extremely small value could increase the number of disassociations (small CCA/SD_{th}) or the number of collisions (small CCA/CS_{th}). On the other hand, an extremely big value could degrade the network performance due to the increased number of exposed nodes (or failure transmissions, as a STA might lock onto frames from neighbouring BSSs).

PAID is a power-saving feature, built on AID of the 802.11n. Contrary to the AID feature, PAID value is not unique for every STA and is carried in the PLCP header. In that way, a STA quickly identifies and drops large frames not intended for it. This allows a STA to reduce its power consumption by switching to sleep or doze mode for the duration of the transmission. Although the initial intention of PAID was to reduce the power consumption, the most important benefit is that the likelihood of an erroneous reception following a successful preamble reception reduces. In particular, a node uses the Extended Interframe Space (EIFS) to initiate a transmission following an erroneous reception, instead of DCF Interframe Space (DIFS), where $EIFS = DIFS + SIFS + ACKTxTime_{LowestMandRate}$. For a transmission from a STA to an AP, PAID is the last 9 bits of the BSSID, while for the reverse link, it combines the AID and the BSSID.

Due to ambiguity issues (a STA might decode a frame destined to an AP), the authors in [22] proposed the BSS Color, as an extension of the PAID feature. According to the BSS Color technique every PLCP header, carries the PAID (PAID is a feature of the Color scheme) or the color id and the uplink id. The color id is used only in a downlink transmission to assist a station in identifying the BSS from which a frame was sent. In an uplink transmission, the PAID feature is sufficient enough to allow the users in distinguishing the BSS by which a frame was transmitted. The later id (*Uplink Indication*) identifies the type of link. Specifically, a value of 1 corresponds to an uplink transmission, while 0 to a downlink transmission. Moreover, the color id values range from 0 to 7, identifying groups of (at most) 8 BSSs and is given to a STA, during the association stage. In particular, there are two approaches that can be followed in a case of color mismatched; either a node defers its transmission until the end of the ongoing transmission, or the use of a 2^{nd} CCA/CS_{th} ($2^{nd} deferral$). In that case, the 11ax node (AP or STA) drops the frame and returns *BUSY* if the *RSSI* is above that threshold, *IDLE* otherwise. That is, a 2^{nd} threshold increases the transmission opportunities for a node.

IV. Experimental Setup

We consider the outdoor dense scenario (Scenario 4), specified in IEEE 802.11 TGax [23]. Furthermore, a large enough simulation time and number of runs were conducted, in order to get more accurate results. We evaluate the aforementioned schemes under full buffer conditions in both directions; using only Uplink or only Downlink traffic. All STAs share the same MAC and PHY characteristics, apart from the DSC and BSS Color schemes, which are enabled only for the 11ax nodes. We assume that the additional color or PAID info are carried in the PLCP header without increasing their transmission time and used in all unicast frames (including ACKs in contrast to [4]). Moreover, we assume that there is no *BSS Color Collision*, and we use a 2^{nd} threshold in case of color mismatched. In our scenario, we consider a 2^{nd} deferral which is equal to the CCA/CS_th. Furthermore, a STA is disassociated from its AP when the packet delivery ratio is more than 99% (referred as disassociation mechanism). The MAC and PHY parameters are listed in Table I.

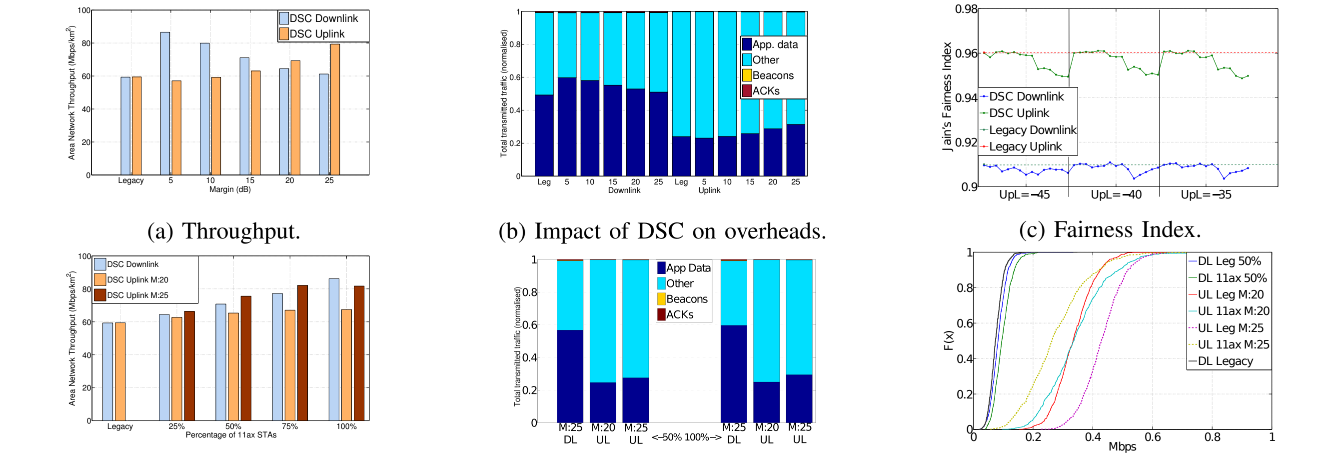
We also apply the wrap-around technique, so that the BSSs from the outer rings have similar behaviour with the one located at the inner rings. As a result the contention and the interference for the nodes located at the outer rings are the same with those on the inner rings. Furthermore, we determine the optimal number of rings required (for the simulation scenarios considered), according to [24]. Fig. 1 illustrates a layout of the simulation scenario.

V. Simulation results

This section presents the performance of a) DSC algorithm, b) BSS Color scheme with and without PAID feature in order to study the impact of EIFS in terms of throughput, and c) a combination of the aforementioned techniques normalised per km^2.

A. DSC performance

First, we evaluate the DSC algorithm for different settings, in a specific scenario where all STAs are 11ax, to



(a) Throughput.

(b) Impact of DSC on overheads.

(c) Fairness Index.

(d) Throughput in the presence of Leg. STAs.

(e) Impact of Leg. STAs on overheads.

(f) Ecdf for Rx and Tx traffic (50% 11ax).

Fig. 2: DSC metrics.

TABLE I: Simulation parameters

Parameter	Value
Scenario	Outdoor (TGax Scenario 4, [23])
Number of APs/STAs	127/1431
Number of rings	6 ([24]) with Wrap-Around
STA density	770 STAs per km^2 (Mobility Disabled)
Channel	TGax channel model ([12])
Shadowing	Disabled
Inter AP distance	130 m
AP/STA Tx Power	20/15 dBm
AP/STA antenna gain	0/-2 dBi
Num. of antennas (AP, STA)	1 (SISO)
Noise figure	7 dB
PHY rate	rate control algorithm - Minstrel [25]
Traffic	CBR, UDP, Full buffer
RTS/CTS	Disabled
Max num. of retransmissions	10
Packet	1464 bytes
Beacon Interval	102.4 ms
CCA/SD, CCA/CS	-82 dBm, -62 dBm

reveal the values that utilize the network throughput. The values used for the DSC are: $UpperLimit(-35, -40, -45)$, $Margin(5, 10, 15, 20, 25)$, and $Decrement(1, 3, 5)$. The DSC is evaluated in the DL and the UL case, while only the CCA/SD_{th} and the CCA/CS_{th} is tuned at a time. In particular, in the DL case, the CCA/SD_{th} has greater impact than the CCA/CS_{th} on the performance, as the STAs do not contend for channel access and thus, are not required to sense the channel. In UL case, as most of the transmitted frames are on the uplink direction, the STAs sense the channel before initiating a transmission. That is, in that scenario, the CCA/CS_{th} severely affects the performance.

Fig. 2a illustrates DSC's throughput against various settings. We only present the results for different $Margin$ values, as the throughput does not vary significantly for different values of the *UpperLimit* or the *Decrement*. The highest throughput in DL and UL scenarios, is achieved for different values of *Margin*; 5 in downlink 5, while 25 in uplink. The closer the CCA/SD_{th} value is to the RSSI from the associated AP, the higher the probability a STA may drop any received frame originated by a neighbouring AP. That is, the probability of a successful transmission from the associated AP increases. On the contrary, larger values of *Margin* for the CCA/CS_{th}, lead to larger carrier sensing ranges, decreasing the number of hidden nodes. However, this might come at the cost of decreasing fairness among the users due to the lower CCA/CS_{th}.

Fig. 2b depicts the impact of the $Margin$ value on overheads. Note that *"Other"* represents the transmitted probes, association requests/responses and the retransmitted data. Overheads decrease with the decrease (increase) of the $Margin$ value for the CCA/SD_{th} (CCA/CS_{th}) in the downlink (uplink). However, even a very high *Margin* value (e.g. 25) is not sufficient enough to compensate for the large number of frame retransmissions in the UL case (approx. 70% of the total transmitted traffic is due to retransmissions).

We now, use the Jain's Fairness Index (JFI), [26], to measure the system fairness for each setting, in terms of transmitted traffic (UL case) and throughput (DL case). Fig. 2c depicts the results for the JFI. The red asterisk stands for the Legacy mode in uplink, while the green for the different settings of DSC. The light blue and the dark blue stand for the legacy and DSC mode, respectively, in downlink. Note that we first gradually increase the *Decrement* value, then the *Margin* and lastly the *UpperLimit*. For example, the first leftmost DSC asterisk corresponds to *DSC(-45,5,1)* while the last rightmost to *DSC(-35,25,5)*, where *DSC(UpperLimit,Margin,Decrement)*. An important outcome is that for small $Margin$ values, the JFI is close to the legacy's one, while for large values, the *UpperLimit* and *RSSI Decrement* parameters affect the fairness index. A low value of the CCA/SD_{th} or CCA/CS_{th}, leads the edge-cell users to lock onto frames originated by neighbouring APs or defer their transmissions more frequently than the others nodes. As a result, fairness issues emerge between the edge-cell users and those located close to their associated AP.

We now evaluate DSC in the presence of legacy STAs, when DSC jointly tunes the CCA/SD_{th} and CCA/CS_{th}, Fig. 2d.

In particular, we use $Margin = 5$ for the CCA/SD_{th}, while 20 and 25 for the CCA/CS_{th}. We observe that as the number of 11ax increases, the network throughput increases too. The CCA/CS_{th} values for the 11ax nodes range from -60 (or -65 when $Margin = 25$) to -82 dBm, reducing the number of hidden nodes (better channel quality). By comparing the 75% to 100% cases in uplink, we can see that high $Margin$ values favour the legacy nodes, as the throughput slightly drops. The throughput gain for $Margin = 25$ compared to the case when $Margin = 20$ is due to the reduced number of overhead, as it is depicted in Fig. 2e.

Even though, the throughput gain increases for $Margin = 25$, it comes at the cost of decreased fairness (in terms of transmitted bits) in uplink, compared to $Margin = 20$, Fig. 2f. In downlink, DSC improves the legacy performance as well, due to the higher packet delivery ratio (PDR). Due to space limitation, we present in Fig. 2f, the results only for the 50% case (50% of the STAs are legacy).

After closely analysing the DSC performance in both DL and UL transmissions, we recommend different *Margin* values for the CCA/SD_{th} and the CCA/CS_{th}. In particular, we propose 5 and 25 (or 20 for preserving fairness) as the values for tuning the aforementioned thresholds, $UpperLimit = -40$, and $Decrement = 5$. In order to use a small *Margin* for the CCA/SD_{th}, the DSC algorithm should use a large value for the *Decrement* parameter (e.g. 5) to result in smaller number of consecutive missed beacons ($X \leq 10$).

B. BSS Color performance

We consider 5 cases for the BSS Color scheme; Legacy, 25%, 50%, 75%, and 100%. In the former case all APs and STAs operate in the legacy mode, while in the other cases, we gradually increase the percentage of the nodes operating in the 11ax mode. In line with the IEEE specification, we consider that the legacy nodes process only the frames transmitted by or destined to legacy nodes (we refer to them as legacy frames). They also, drop the colored frames and set *CCA IDLE* when the predicted duration based on the *TxTime* has elapsed. It should be noted that an 11ax node processes not only the frames destined to it, but the legacy frames too.

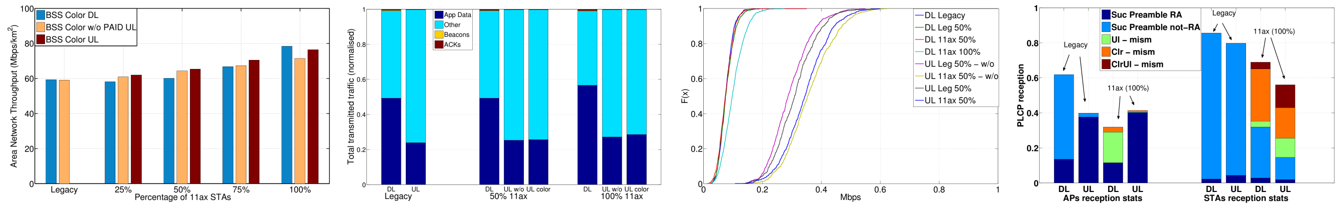
Fig. 3a depicts the performance of the BSS Color scheme in the presence of legacy STAs when PAID is used in the unicast frames transmitted by the APs and when it is not (*w/o PAID* on the DL frames). We present the results in the DL case only for the BSS Color scheme, since its performance is similar to the *BSS Color w/o PAID*. This is due to the fact, that STAs benefit from the use of PAID only when they transmit frames. To clarify, in the UL case, a STA drops every ACK originated by its associated AP and destined to another STA. In that way, a STA initiates a transmission following a successful reception of the ACK preamble using DIFS instead of EIFS, thus improving the performance. In the DL case an AP has to process all frames (ACKs in our DL scenario) originated by its associated STAs, and drop all the other frames (PAID carries a different BSSID) originated by a neighbouring BSS. In that case, a STA drops a data frame intended to a different STA and it transmits an ACK only if the frame was intended to it. A potential throughput gain of PAID could be also observed in a mixed-traffic (UL and DL transmissions) scenario, however in this work we do not consider such a scenario.

In the UL case, we observe that the performance gradually improves with the increase in the percentage of the 11ax STAs. This is because the likelihood of at least one transmission per BSS increases. Furthermore, PAID enhances the throughput by improving the PDR (Fig. 3b, *"Color"* bar), which validates our previous argument about the benefits of PAID.

As depicted in the Fig. 3a, BSS Color increases the number of concurrent transmissions within a network, we observe that when the number of legacy nodes is more than the 11ax in downlink, the network throughput slightly degrades compared to the legacy mode. This might be due to the high number of disassociated STAs (edge-cell users) for the legacy mode, improving the network throughput or an AP drops all the colored frames originated by neighbouring BSSs, while it locks onto all legacy frames with *RSSI* greater than the CCA/SD_{th}. As the percentage of the 11ax nodes increases, the likelihood an AP to lock onto a legacy frame originated by a neighbouring BSS drops. That means that an AP might sense the channel as *IDLE*, initiating a transmission to a node (legacy or not) which has already been locked onto a legacy frame. In the above example, the RSSI of the legacy frame is not sufficient enough to trigger one of the *CCA* thresholds and block the AP from transmission, while one of the colored frames might be above the CCA/SD_{th} but still not to satisfy Eq. 1. The only difference as the number of 11ax increases, is that the likelihood of a legacy frame transmission drops. Note that when there is a balance between the number of legacy and 11ax STAs, the network throughput is similar to the *"Legacy"* case. Moreover, the PDR for these two cases is the same, while it further increases as the 11ax are more than the legacy, Fig. 3b. BSS Color preserves the fairness among the legacy and the 11ax STAs, as we can see in Fig 3c for the *50%* case (in DL). However, as the number of concurrent transmissions increase, the Color favours the nodes located close to the associated AP, due to the high interference that the edge-cell users face, from neighbouring APs. This is validated by observing the steep incline of the slope *"DL 11ax 100%"*.

Note that the 5 leftmost ecdfs in Fig 3c, stand for the throughput in downlink, whereas the 4 rightmost ecdfs for the transmitted bits in uplink when PAID is used and when it is not. It is worth noting that PAID feature enhances the fairness between the users in terms of transmission opportunities. If an error occurs at the payload, following a successful reception of a preamble will not affect a STA if it is not the intended recipient of that frame. In that way, the group of STAs that will initiate a transmission after EIFS reduces, preserving fairness among the users of the same BSS. Moreover, in UL case, as we expect the color technique favors the STAs that use it, increasing their transmission opportunities. This can be observed by comparing the throughput per legacy and 11ax STA in UL for the *50%* case (Fig. 3c).

Fig. 3d illustrates the successfully received PLCP headers



(a) Throughput. (b) Impact on overheads. (c) Ecdf for Rx and Tx traffic. (d) PLCP reception stats.

Fig. 3: BSS Color (& BSS Color *w/o PAID*) metrics.

over the total detected preambles. *"Suc PLCP RA"* represents the percentile of the correctly received PLCP headers that are destined to that node, whilst *"Suc PLCP not-RA"* the percentile of the successfully received PLCP headers that are intended for a different node. In particular, the percentile of these two categories, represent the percentage of the frames that a node locks onto. *"UL - mism"* stands for the case where the *Uplink Id* is not correct. It occurs whenever an AP correctly receives a frame from another AP, or a STA from another STA from the same BSS. *"Clr - mism"* stands for the Color Mismatched, namely the successfully received PLCP headers that are sent by a neighbouring BSS, while the *Uplink Id* is correct. *"ClrUl - mism"* shows the percentage of the correctly received PLCP headers by a STA that are originated by a STA belonging to a neighbouring BSS. To summarise, a node is interested only in the *"Dark blue"* PLCP headers.

Three important conclusions can be drawn from that figure in downlink. First, the interference caused by neighbouring APs (*"UL - mism"* for the APs and *"Clr - mism"* for the STAs). Second, the significant high percentage of *"Clr - mism"* in an AP, compared to *"Suc PLCP RA"*, which indicates the importance of the color field in both directions (in UL the color corresponds to the PAID). Lastly, the amount of frames that a STA proceeds which are not destined to it (*"Suc PLCP not-RA"*). The throughput gain of BSS Color scheme against BSS Color *w/o PAID* derives from the fact that a STA will drop these packets (due to PAID).

Due to the fact that the transmission probability per BSS increases, an AP mostly locks onto frames transmitted by its associated STAs. This can be observed in Fig. 3d for the uplink transmissions. Furthermore, we can see that a STA experiences the same "interference"from the STAs belonging on the same and neighbouring BSSs.

C. Combining the BSS Color with the DSC

We now apply the DSC scheme along with the BSS Color, in order to compensate for the high interference that the latter technique introduces (especially in the UL case). We use the following settings for the DSC scheme; *DSC(-40, -5, -20, 5)* and *DSC(-40, -5, -25, 5)*, where $DSC(Upperlimit, Margin{-}CCA/SD_{th}, Margin{-}CCA/CS_{th}, Decrement)$.

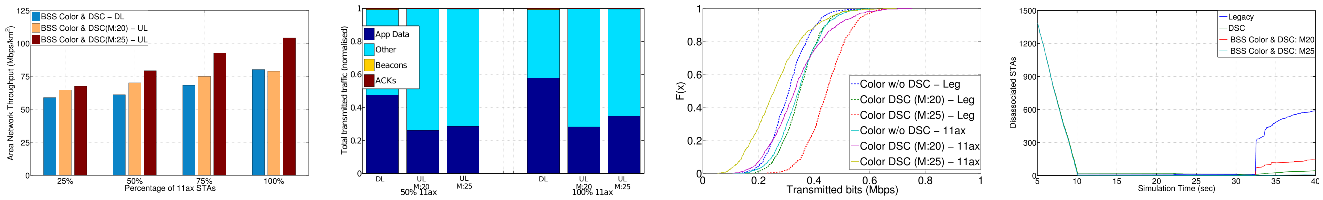
Fig. 4a illustrates the performance of the BSS Color, when it is used along with the DSC algorithm. By tuning the CCA/SD_{th} and the CCA/CS_{th} accordingly, the total network throughput increases (compared to Fig. 3a), and the PDR (Fig. 4b) too. In the DL case, the throughput gain is much lower compared to the UL case, because in BSS Color scheme an 11ax node drops all colored frames originated by a neighbouring BSS. Thus, DSC additionally drops only a small number of frames (i.e. broadcasts with RSSI below CCA/SD_{th}) from the neighbouring BSSs. However, the network throughput in the DL case, is still lower than the one when only DSC is applied (Fig. 2a). When only DSC is used, a transmission from an AP might prevent the neighbouring APs from transmitting, as the DSC applies only at the STAs. On the contrary, the BSS Color scheme does not block its neighbouring APs from transmitting, increasing the interference levels.

A lower CCA/CS_{th} achieves higher throughput gain in uplink compared to the cases where the spatial reuse schemes are used individually. This is due to the higher carrier sensing range, resulting in less hidden nodes. However, that comes at the cost of deteriorating the fairness among the users.

We also, observe in Fig. 4c that as the number of the 11ax increases, the fairness among the users deteriorates, while the throughput per station increases. On the contrary, the legacy performance slightly improves, compared to the BSS Color scheme where the DSC mechanism is not used. This is mainly, due to the lower CCA/CS_{th} for the 11ax STAs. A value of 25 for the $Margin$ improves the legacy performance, due to the lower CCA/CS_{th} for the 11ax STAs and the higher PDR.

Fig. 4d presents the number of the disassociated STAs in the UL case, for the first 40 seconds of the simulation. We present only the UL case, because it is the worst case in terms of contention. We observe that when the data traffic starts (30^{th} second), the number of the disassociated stations increases. In particular, more than 25% of the STAs disassociate from their APs in the Legacy mode. On the contrary, when DSC is applied, the stations mostly lock onto frames originated by their associated APs, leading to less disassociations. Another important outcome is that a $Margin$ value of 20 for the CCA/CS_{th} is not enough to compensate for the high interference level introduced by the BSS Color scheme. When $Margin = 25$, the number of the disassociated STAs throughout the simulation remains constant. However, the high number of the disassociated STAs for the legacy case, may be due to the use of the disassociation mechanism.

After analysing the results, we argue that the Color scheme with the DSC algorithm can significantly enhance the network



(a) Throughput. (b) Impact on overheads. (c) Ecdf for Tx traffic (50% 11ax). (d) Disassociated STAs.

Fig. 4: BSS Color along with DSC, metrics.

throughput, and the spatial reuse. We recommend 25 as the optimal value for the $Margin$ of the CCA/CS_{th} (*DSC(-40, -5, -25, 5)*). However, this might come at the cost of slightly decreased fairness among the users. In order to compensate for the high interference that the edge-cell users experience, especially in the UL case, a TPC algorithm should be used in the APs and 11ax STAs.

VI. Conclusion

In this paper, we investigated the performance of DSC algorithm, BSS Color scheme, PARTIAL-AID feature, and a combination of the aforementioned techniques. We evaluated them for both uplink and downlink transmissions, in a dense network of 802.11ax and legacy nodes. By utilizing the DSC scheme and using different *Margin* values for the CCA/SD_{th} and the CCA/CS_{th}, the network throughput improves and the fairness between the nodes can be preserved. We showed that only when the number of 802.11ax STAs is higher than the legacy, the BSS Color technique enhances the network performance. We also, investigated the performance of PAID, which improves the throughput by reducing the erroneous received frames. By jointly using the aforementioned techniques, we showed that the network throughput can be further improved, especially for the uplink transmissions. A future study will include a performance evaluation of TPC and DSC algorithms at the APs (in Scenario 3 and 4) in combination with the aforementioned techniques, aiming at reducing the interference between the neighbouring BSSs.

Acknowledgment

We would like to acknowledge the support of the University of Surrey 5GIC (http://www.surrey.ac.uk/5gic) members for this work.

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