Control OBSS/PD Sensitivity Threshold for IEEE 802.11ax BSS Color

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***Abstract*—IEEE 802.11ax Spatial Reuse (SR) is a new category in the IEEE 802.11 family, aiming at improving the spectrum efficiency and the network performance in dense deployments. The main and perhaps the only SR technique in that amendment is the Basic Service Set (BSS) Color. It aims at increasing the number of concurrent transmissions in a specific area, based on a newly defined Overlapping BSS/Preamble-Detection (OBSS/PD) threshold and the Received Signal Strength Indication (RSSI) from Overlapping BSSs (OBSSs). In this paper, we propose a Control OBSS/PD Sensitivity Threshold (COST) algorithm for adjusting OBSS/PD threshold based on the interference level and RSSI from the associated recipient(s). In contrast to the Dynamic Sensitivity Control (DSC) algorithm that was proposed for setting OBSS/PD, COST is fully aware of any changes in OBSSs and can be applied to any IEEE 802.11ax node. Simulation results in various scenarios, show a clear performance improvement of up to 57% gain in throughput over a conservative fixed OBSS/PD for the legacy BSS Color and DSC.**

I. Introduction

Similar to cellular technology, Institute of Electrical and Electronics Engineers (IEEE) 802.11 Wireless Local Area Networks (WLANs) are evolving to keep pace with the rapid changes and new user-expectations/needs that telecommunications industry faces. The exponential growth in mobile data traffic, number of devices connected to the internet, new use-cases, and user-requirements are the main challenges for the next generation networks [1].

Due to the success and advantages that WLAN technology offers, it is expected that it will play a key role in forming the next-generation networks. In particular, it is a cost-efficient solution that can easily be deployed (e.g. apartments, offices, etc.), providing access to the internet at high data rates. However, the unplanned and unmanaged Access Point (AP) deployment, exacerbates network performance due to interference issues.

To address the demands and new challenges that WLANs will face in the 2.4 GHz and 5 GHz frequency bands, IEEE 802.11ax [2] was introduced in 2014 and is under active development. It is expected to be finalised within the second half of 2019.

In contrast to its predecessors aiming at enhancing link throughput, Task Group 802.11ax (TGax) focuses on improving spectrum efficiency and area throughput in dense WLAN scenarios, whilst reducing power consumption for portable devices [3]. Furthermore, this amendment will incorporate additional bands between 1 and 7 GHz as they become available.

Backward compatibility is one of the main requirements in the IEEE 802.11ax specification, since heterogeneous devices are expected to be operating in the same frequency. Other features introduced in this amendment so far, include advancements for small cell networks (higher order of modulation, 1024-QAM), multiple-antenna techniques (Downlink/Uplink Multi-User Multiple-Input-Multiple-Output (DL/UL MU-MIMO)), efficient use of channel resources (DL/UL Orthogonal Frequency Division Multiple Access (OFDMA)), and spatial reuse (SR) techniques [4]–[6]. SR mechanisms aim at increasing the number of concurrent transmissions within a given area, such that area throughput and spectrum efficiency improve. In general, SR comprises those schemes that adapt carrier sensing or use a transmit power control (TPC). Although, various SR schemes have been widely studied for wireless networks [9]–[11], nevertheless, only the usage of a TPC is standardised by IEEE 802.11h-2003. In particular, IEEE 802.11h-2003 defines the rules for the maximum transmit power in a region.

This work focuses on IEEE 802.11ax SR mechanism and the latest advancements presented in TGax. The SR scheme that is currently included in IEEE 802.11ax amendment, namely Basic Service Set (BSS) Color, is an advanced technique that only recently was proposed [7]. In that sense, SR is a completely new feature, incorporated in IEEE 802.11ax amendment. Furthermore, we present an algorithm to further enhancing BSS Color performance and compare their performance in various scenarios identified in TGax. The ns-3 simulation tool [8] is used to carry out this study, wherein the proposed new algorithm and supporting features are implemented.

The rest of the paper is organised as follows. Section II

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presents related work and describes BSS Color scheme. Section III overviews the concept and design of the proposed algorithm for further improving BSS Color performance, while Section IV presents the simulation scenario and Section V analyses the simulation results. Finally, Section VI concludes the paper.

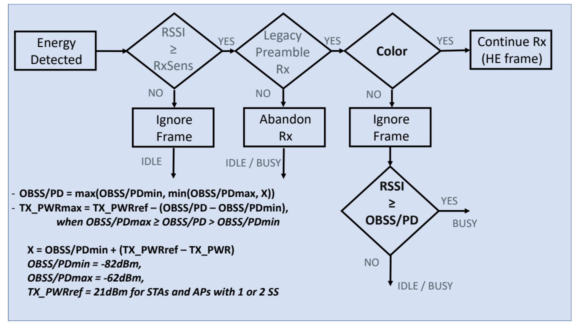


Fig. 1. A simple flow chart of BSS Color frame reception.

II. Related Work

IEEE 802.11 is an asynchronous technology that relies on random-access methods for granting access and transmitting over the wireless medium. It uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, which implies that every node senses the channel prior a transmission. If the energy sensed on the channel exceeds the Clear Channel Assessment (CCA) threshold, then the channel is identified as *BUSY* and the transmission is deferred. Otherwise, the channel is declared as *IDLE* and the node proceeds to a frame transmission.

It is clear from the above that the probability of a transmission is highly related to the value of CCA threshold. A low threshold results in low transmission opportunity (large carrier sensing range), whereas an aggressive value can lead to higher transmission opportunity. Similar to CCA threshold, the level of transmit power also affects the probability of a transmission. In particular, the use of high transmit power level, makes the transmission detectable by nodes located far away, which affects their transmission opportunities.

Various approaches have been followed for adjusting the CCA threshold. The algorithm presented in [12], [13], incorporates the IEEE 802.11k amendment to obtain the statistics needed for the threshold adjustment. Moreover, nodes periodically transmit their measurement reports to the AP, which in turn processes all reports and broadcasts this information through the beacons. An area-based scheme for adjusting CCA threshold was proposed in [14], [15], where the use of Request-to-Send/Clear-to-Send (RTS/CTS) frames or a wireless controller, respectively, for defining the area that a node belongs to, is investigated. A decentralised approach, based on beacons' received signal strength indication (RSSI) is followed in [16], [17]. A *Margin* value then subtracted from the recorded beacons' RSSI, while an upper limit (UpperLimit) is also used, corresponding to the maximum CCA threshold. In particular, the algorithm from [16], namely Dynamic Sensitivity Control (DSC), was proposed in TGax [18] for improving SR, but did not get incorporated in the amendment [19].

On the other hand, BSS Color is the SR technique that was adopted by IEEE 802.11ah and included in the IEEE 802.11ax amendment. Its main goals are reducing power consumption and enhancing spectrum efficiency by the early identification of the BSS that a frame is transmitted from. The BSS Color is a 6-bit value carried in the High Efficiency Signal (HE-SIG) field along with the 1-bit UL_FLAG field, which identifies the link direction of a frame (i.e. DL/UL). BSS Color value ranges from 1 to 63, while 0 indicates that BSS Color is not used. Color information is distributed to nodes during the association stage, and it may change during operation, if a color collision is detected.

A simple flow chart of BSS Color preamble reception is illustrated in Figure 1. A node can abandon reception when a color mismatch (Color $\neq$ 0) is detected and based on the RSSI to initiate a transmission. In particular, the RSSI is compared against a newly defined threshold, namely Overlapping BSS Preamble Detection (OBSS/PD), which was introduced to control the number of concurrent transmissions and interference level. It mimics RTS/CTS behaviour but without the exchange of control frames. In case BSS Color is not used, frame reception is not abandoned and it follows the legacy procedure.

OBSS/PD threshold can be adjusted, during operation, in a decentralised way according to transmit power level as:

$$OBSS/PD = max(OBSS/PD_{min}, min(OBSS/PD_{max}, X)) \tag{1}$$

where $X, OBSS/PD_{min}$, and $OBSS/PD_{max}$ are depicted in Figure 1. Thus, the probability of concurrent inter-BSS transmissions is controlled by the value of this threshold. It increases with the increase of OBSS/PD, while an extremely low value (i.e. -82 dBm) diminishes the benefits of using BSS Color in terms of transmission opportunities.

Moreover, if a node selects a specific OBSS/PD threshold, then the maximum transmit power level is determined according to:

$$TX\_PWR_{max} = TX\_PWR_{Ref} - (OBSS/PD - OBSS/PD_{min}) \tag{2}$$

when $OBSS\_PD_{max} \geq OBSS\_PD > OBSS\_PD_{min}$. The default values for the remaining parameters are also depicted in Figure 1. The main

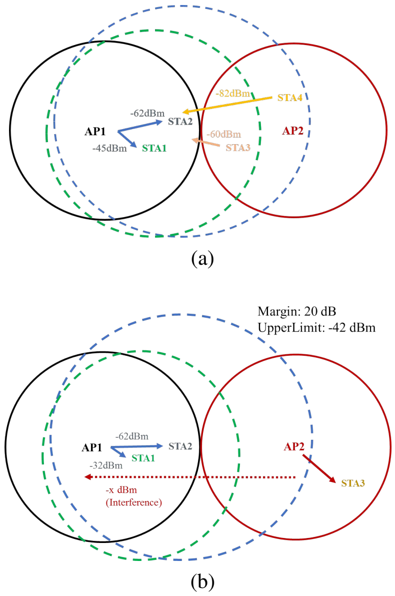


Fig. 2. DSC limitations a) first case and b) second case.

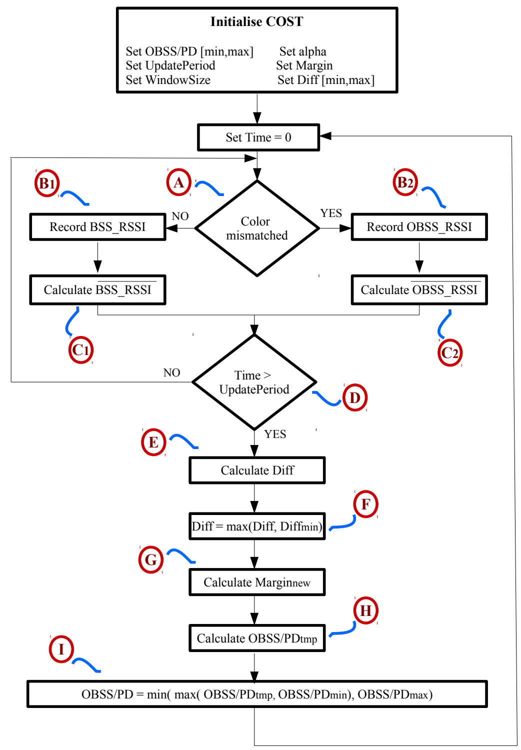


Fig. 3. Flow chart of COST algorithm operating at both APs and STAs.

idea of adjusting OBSS/PD with transmit power is to mitigate interference to OBSSs.

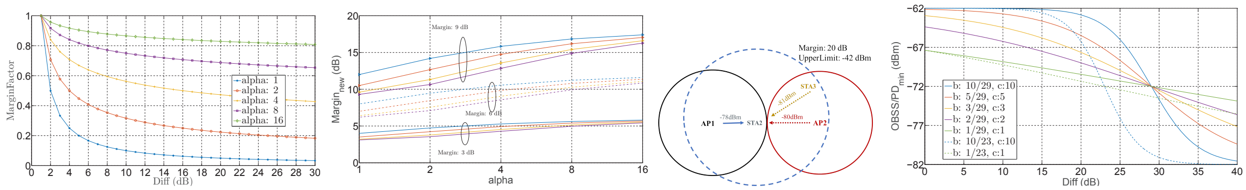
Another addition in the amendment due to BSS Color, is the support of two Network Allocation Vectors (NAVs) per device. One for intra-BSS (intra-BSS NAV) and one for inter-BSS frames or those frames that cannot be identified (basic NAV). The channel is identified as *IDLE* when both NAV timers are zero, and *BUSY* otherwise. Furthermore, the basic NAV is not updated when the inter-BSS RSSI is below the OBSS/PD threshold, even if the frame duration exceeds the current basic NAV. Our previous works in [20], [21] include the evaluation of BSS Color in dense indoor and outdoor scenarios. Even though, BSS Color scheme aims at enhancing network throughput and spectrum efficiency, throughput loss may be observed due to the high interference level [21]. Interference level can be controlled by tuning the OBSS/PD and transmit power, however, as yet no mechanism has been defined in the amendment on how to set them.

Although, DSC was originally proposed in TGax as an SR technique for tuning CCA thresholds, it was also, recently proposed for tuning OBSS/PD [22]. The main drawback for DSC is that stations (STAs) close to the AP have higher probability of accessing the medium due to higher RSSI that results into smaller carrier sensing range [23]. This case is illustrated in Figure 2a, where STA2 transmits only when STA4 does not transmit, even though a concurrent transmission from these STAs could be successful. Moreover, assuming that DSC is applied for OBSS/PD, then in a scenario such as the one depicted in Figure 2b, STA1 initiates a transmission to AP1 whereas STA2 must defer its transmission due to lower OBSS/PD. Assuming that Signal-to-Interference-plus-Noise ratio (SINR) at AP1 is the same from both STA1 and STA2 (i.e. $Tx\_PWR_{STA1} = 1dBm, Tx\_PWR_{STA2} = 21dBm$), then by applying Equation 2 or DSC, it becomes obvious that transmission opportunity for cell-edge users further decreases for the same SINR level and the probability of a false alarm increases too. Lastly, DSC applies only at STAs and does not take into account any changes on the OBSSs, hence it does not fully exploit BSS Color.

III. Control OBSS/PD Sensitivity Threshold (COST)

To overcome DSC's limitations, we present Control OBSS/PD Sensitivity Threshold (COST) algorithm, which sets OBSS/PD based on the inter-BSS and intra-BSS RSSI. COST is designed to operate at both APs and STAs. The main goals for COST are: i) protecting ongoing transmissions, ii) preserving cell-edge users from starvation, and iii) preserving fairness for all nodes in terms of channel contention (roughly the same probability of transmission for all nodes). A flow chart of COST algorithm is depicted in Figure 3. COST is initialised following a conservative approach (OBSS/PD is set to its minimum value) for detecting majority of nodes in its vicinity. Its basic functionalities are highlighted below.

The first step (*A*) is to check BSS Color value in the HE-SIG-A field and identify whether the frame is



(a) (b) (c) (d)

Fig. 4. COST parameters: a) an example for *Margin Factor*, b) an example for $Margin_{new}$, c) a scenario example for the optional feature of COST at STAs, and d) an example of $OBSS/PD_{min}$.

intra-BSS (BSS) or inter-BSS (OBSS). This step is also included in the HE frame reception, nevertheless, nodes now (steps *B1, B2*), record the RSSI before abandoning or continuing the reception. In steps *C1, C2*, nodes accumulate the recorded RSSI for BSS and OBSS frames using any moving average scheme, such as Exponential Moving Average (EMA). The *WindowSize* defines the window size for the moving average scheme. If the elapsed time has exceeded *UpdatePeriod*, COST proceeds to step *E*, otherwise it awaits for the next frame to be received. For example, *UpdatePeriod* could be equal to *N* beacon intervals.

In step *E*, the following equation is applied:

$$Diff = \left|\overline{BSS\_RSSI} - \overline{OBSS\_RSSI}\right| \tag{3}$$

The main idea behind Equation 3 is the identification whether BSS STAs are closer to or not to OBSS interferers rather their BSS recipient(s), an information that is used in step *G*. Step *F* is essential to avoid a division by zero in step *G*, where $Margin_{new}$ is calculated according to:

$$Margin_{new} = \frac{Margin}{Diff^{alpha-1}} + Margin \tag{4}$$

where *alpha* is an integer value that is introduced to further increase *Margin* value. In some cases, a higher *Margin* might be required for a successful transmission to a cell-edge user or when high data rates are used. Thus, instead of the APs advertising the new *Margin* values, they can tune *alpha* instead. Figure 4a presents the $MarginFactor = 1/Diff^{alpha^{-1}}$, whereas Figure 4b the $Margin_{new}$ value for various *alpha* and *Diff* values. Four outcomes can be observed from these Figures. First, a high *alpha* value results to high $Margin_{new}$ in respect to the advertised *Margin* even for large *Diff* values ($Margin_{new} > 1.8 * Margin$). Secondly, as *alpha* increases, the *Diff* value has low impact on the final $Margin_{new}$ value. Thirdly, high *Diff* values have negligible effect on $Margin_{new}$ irrespective of *alpha* and *Margin*. This can be observed by comparing the yellow and purple lines in Figure 4b. Lastly, the higher *Margin* is, the higher the difference of two $Margin_{new}$ values for different *Diff* values.

Due to the nature of the wireless deployments, OBSS STAs' RSSI might be higher than BSS STAs' RSSI at an AP, either because they are closer or due to shadowing. APs must ensure that BSS STAs will successfully receive the frames in the presence of OBSS STAs, hence the following calculation is performed in step *H*:

$$OBSS/PD_{tmp} = \min(\overline{BSS\_RSSI}, \overline{OBSS\_RSSI}) - Margin_{new} \tag{5}$$

Before setting OBSS/PD, the threshold is confined between the minimum and maximum OBSS/PD thresholds, which can be seen in step *I*. Note that, to reduce implementation complexity whilst preserving most of the gains that COST algorithm offers, some steps can be skipped for COST operating at STAs. For example, the recording of RSSI from BSS frames and step *G* can be skipped, while $\overline{BSS\_RSSI}$ can be replaced with $\overline{OBSS\_RSSI}$ in step *H*.

An additional (optional) step at STAs for setting the minimum OBSS/PD threshold could also be deployed for preserving transmission opportunity for cell-edge users. A cell-edge user can benefit from a higher OBSS/PD threshold than a user not located at the cell-edge, when roughly the same interference level is sensed by the two users. The main idea is to define a function that preserves cell-edge users from using an extremely conservative threshold, which could lead to extremely low transmission opportunities. For example, the following equation can be followed for setting the minimum OBSS/PD threshold:

$$OBSS/PD_{min} = OBSS/PD_{def} + \frac{Diff_{max}}{1 + \exp(b * x - c)} \tag{6}$$

where $OBSS/PD_{def}$ is the default minimum value for OBSS/PD (i.e. -82 dBm for 20 MHz channel bandwidth), $Diff_{max}$ is the maximum value that can be subtracted from $OBSS/PD_{def}$. Parameter x could be either the average beacons' RSSI from the associated AP or *Diff*. *Diff* tends to zero as a user moves away from the AP, since interference level inclines whereas RSSI from the AP decays, assuming that neighbouring BSSs exist. Moreover, the parameters b and c can be adjusted accordingly, based on the decay rate or threshold

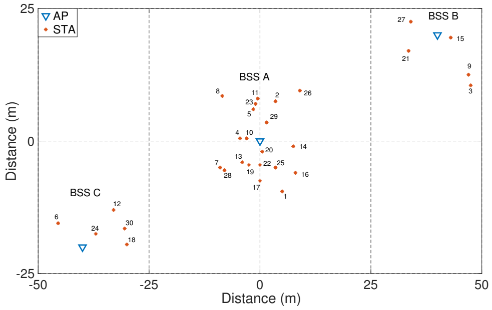


Fig. 5. Simulation Scenario (Box 5).

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Scenario	Indoor (Box5)
Channel Model	TGax SCE3
Number of BSSs	3
Frequency Band [GHz] / Bandwidth [MHz]	2.4 / 20
Shadowing [dB]	5
Physical Capture Model	800ns/10dB [21]
AP/STA Tx Power [dBm]	20/15
AP/STA Antenna Gain [dBi]	0/-2
Number of Antennas	1
Noise Figure [dB]	7
PHY rate [data]	HE-MCS0, HE-MCS5
PHY rate [control]	HE-MCS0
Traffic	Full Buffer
RTS/CTS	Disabled
Max Retransmissions	10
Contention Window [min,max]	[15,255]
Packet at APP Layer [bytes]	1472
Max A-MPDU [no. of frames]	32
TxOP [ms]	5.484 (AC_BE)
Beacon Interval [ms]	102.4
CCA/SD, CCA/ED [dBm]	-82,-62
OBSS/PD (min, max) [dBm]	(-82, -62)
Simulation Time per run [s]	200 (20 Runs)

we need to achieve. An example of the decrement factor of Equation 6 for $Diff_{max} = 20$ dB and $x = Diff$ is illustrated in Figure 4d. *Diff* shall be zero if $\overline{OBSS\_RSSI} > \overline{BSS\_RSSI}$. Note that the values for b and c highly affect the decline rate and the breakpoint.

IV. Experimental Setup

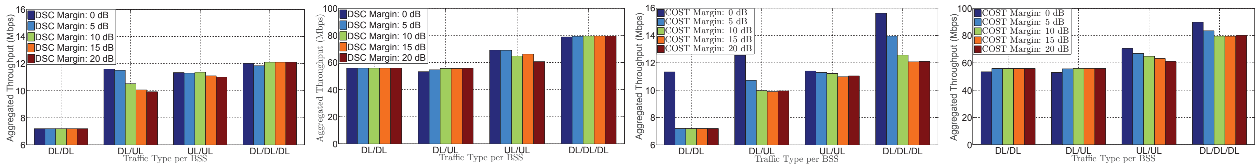
We consider the scenario illustrated in Figure 5 to evaluate BSS Color, DSC, and COST schemes in terms of throughput and fairness. In particular, this scenario corresponds to the Box 5 scenario from the list of TGax baseline scenarios [25]. Four different cases are considered, including both DL and UL traffic and different patterns of the BSSs that are being enabled, following the procedure as described in [26]–[28]. In particular, the first three cases (i.e. *DL/DL*, *DL/UL*, *UL/UL*) refer to the scenarios when only BSSs A and B are enabled, whereas the last case (*DL/DL/DL*) refers to the scenario when all the BSSs are enabled. We also assume no color collisions, which means that BSS Color is unique for each BSS. Preamble reception and capture effect are also modelled, following the procedure described in [19] and in [21], respectively. Two different data rates are used, the robust High-Efficiency Modulation and Coding Scheme 0 (HE-MCS0) and HE-MCS5, whereas the propagation model is the one defined for Scenario 3 (SCE3) in TGax. The simulation parameters used in this study are listed in Table I. Note that when DSC is enabled, Equation 1 is applied at the APs, since DSC operates only at STAs. Moreover, a warm-up period is also considered, hence, the statistics are collected from the last 50 seconds per simulation run.

V. Simulation Results

This section presents the performance evaluation of a) DSC and COST for various *Margin* values and b) against BSS Color (enabled and disabled) in terms of fairness and aggregated throughput. For the fairness, the Jain's Fairness Index (JFI) [24] is considered and is based on the average user throughput per BSS.

Figure 6 illustrates the aggregated throughput of DSC and COST schemes for various *Margin* values. We can observe that COST outperforms DSC in all cases, especially when a DL flow is enabled, since DSC operates only at STAs. The highest throughput for both COST and DSC when HE-MCS0 is used, is achieved for aggressive OBSS/PD thresholds (*Margin = 0*). On the other hand, when higher MCS is applied (HE-MCS5), the highest throughput is not always achieved for an aggressive OBSS/PD threshold. This is due to the higher SINR requirement for HE-MCS5, where a more conservative threshold might be required for protecting transmissions. For example, if we compare the *DL/DL* case, we can observe that two concurrent DL transmissions can be successful when HE-MCS0 is applied, but not when HE-MCS5 is used.

Figure 7 depicts a comparison of the highest throughput achieved for COST and DSC with the default BSS Color and BSS Color disabled performances. Six important conclusions can be drawn from that Figure. First, with *BSS Color ON*, a throughput gain can be observed compared to *BSS Color OFF*. However, it is highly affected by the traffic type and scenario, since the use of a conservative OBSS/PD threshold might have no impact on network performance as it can be seen for the *DL/DL* case. Secondly, a higher throughput gain can be achieved by tuning OBSS/PD threshold. Thirdly, COST achieves the highest throughput gain in all the cases among the aforementioned techniques, with the exception of the *UL/UL* scenario. In particular, up to 57% throughput gain can be observed for the *DL/DL* case when COST is applied, compared to DSC, *BSS Color ON*, and *BSS Color OFF* techniques. Fourthly, throughput loss for the *UL/UL* is observed when BSS Color is enabled. This is due to the high number of contending STAs in BSS A,



(a) (b) (c) (d)

Fig. 6. Aggregated throughput for various *Margin* values of: a) DSC for HE-MCS0, b) DSC for HE-MCS5, c) COST for HE-MCS0, and d) COST for HE-MCS5.

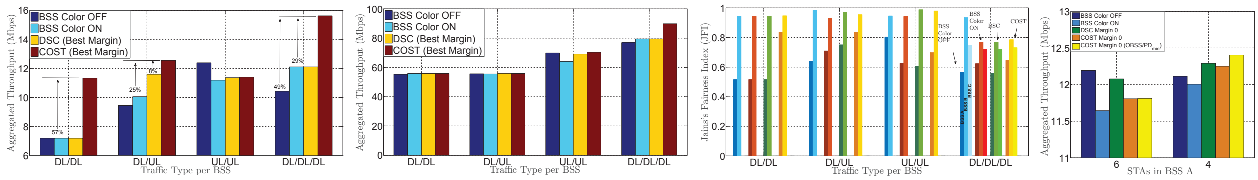
as it is explained in the next paragraph. Fifthly, fairness is highly affected due to the enabling of BSS Color as it can be observed in Figure 7c. Apart from the *UL/UL* case, in all other simulated cases, fairness among BSSs improves by the use of COST, as transmission probability among BSSs is roughly the same (e.g. *DL/DL/DL*). Note that JFI is presented only for HE-MCS0, since it does not vary significantly for HE-MCS5. Lastly, the small throughput gain in *DL/DL* for HE-MCS5 when BSS Color is enabled, is due to Extended Interframe Spacing (EIFS) that is applied after a failed reception for protecting the transmission of ACKs. In particular, when BSS Color is enabled and after a color mismatch, a node abandons the reception and does not experience EIFS. Note that EIFS has no impact in throughput when HE-MCS0 is used, as that data rate is more resilient to low SINR.

We now study the *UL/UL* case when the aforementioned techniques are applied, Figure 7d. When BSS Color is enabled, the number of contending STAs in BSS A increases compared to *BSS Color OFF*, especially for COST algorithm. On the other hand, when BSS Color is disabled, the STAs in BSS A that are located in between BSS A and BSS B may sense the channel as *BUSY* when an UL transmission in BSS B occurs, reducing the number of contending STAs in BSS A. An efficient way to reduce the collision rate in BSS A is by tuning the contention window along with CCA for intra-BSS frames. However, since tuning contention window size and CCA threshold are out of the scope of this paper, we reduce the contention by reducing the number of STAs in BSS A. In particular, we first reduce the number of STAs in BSS A to 6 (*STAs (1, 2, 5, 7, 25, 26)*) and to 4 (*STAs (5, 7, 25, 26)*). A *Margin* value of 0 for both DSC and COST is used, while Equation 6 is also applied to limit the $OBSS/PD_{min}$ value. The values used for adjusting $OBSS/PD_{min}$ are: $OBSS/PD_{def} = -82$, $b = 3/29$, and $c = 3$. As the number of STAs within BSS A decays and the contention decreases, BSS Color performance improves. DSC outperforms COST due to the fact that the former algorithm reduces transmission opportunity for the cell-edge user, resulting in lower contention. However, when the $OBSS/PD_{min}$ is accordingly adjusted (contention may reduce), then throughput gain for COST is higher and outperforms DSC when the number of STAs in both BSSs is roughly the same.

After analysing the results, we argue that OBSS/PD threshold should be adjusted similar to CCA in order to improve network performance and to fully exploit BSS Color. The value of *Margin* for tuning OBSS/PD is an important parameter for both the DSC and COST algorithms and has significant impact on throughput gain. COST achieves higher throughput gain than DSC in most of the cases (up to 57% for *DL/DL* case), as it takes into account changes occurring in OBSSs. On the other hand, by preserving fairness for users in a BSS, contention among them increases, hence, the throughput loss observed in Figure 7a for the *UL/UL* case. However, contention among users can be managed by other means specifically designed to cope with it (i.e. CCA, contention window etc.).

VI. Conclusion

In this paper, we investigated the performance of a newly introduced IEEE 802.11ax feature, i.e. BSS Color and the impact of OBSS/PD threshold in various cases. We also proposed COST, an algorithm for adjusting OBSS/PD at both APs and STAs that does not require major modifications in MAC layer. COST adjusts OBSS/PD based on the interference level observed and the RSSI from the associated recipient(s). It was also compared against DSC, an algorithm that was initially proposed for adjusting CCA, but was also proposed in TGax for OBSS/PD threshold adjustment. We showed that COST outperforms the aforementioned schemes (up to 57% in terms of throughput gain) in most of the simulated cases, while preserving fairness among the users. On the other hand, COST increases the transmission opportunities for STAs (roughly the same probability for all users within a BSS), resulting in higher contention level too. However, user contention can be managed by other means that are specifically designed to deal with it, such as the CCA threshold and the contention window size. Directions for future study include the study of COST in dense TGax scenarios, and its operation in completely local way (i.e. *Margin* value is determined locally).



(a) (b) (c) (d)

Fig. 7. Comparison of BSS Color ON/OFF with DSC and COST schemes in terms of throughput and fairness: a) aggregated throughput for HE-MCS0, b) aggregated throughput for HE-MCS5, c) JFI for HE-MCS0, and d) study of *UL/UL* case for different BSS A STA density.

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