Exploiting the Capture Effect on DSC and BSS Color in Dense IEEE 802.11ax Deployments

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ABSTRACT

Future wireless local area networks (WLANs) are expected to serve thousands of users in diverse environments. To address the new challenges that WLANs will face, and to overcome the limitations that previous IEEE standards introduced, a new IEEE 802.11 amendment is under development. IEEE 802.11ax aims to enhance spectrum efficiency in a dense deployment; hence system throughput improves. Dynamic Sensitivity Control (DSC) and BSS Color are the main schemes under consideration in IEEE 802.11ax for improving spectrum efficiency. In this paper, we evaluate DSC and BSS Color schemes when physical layer capture (PLC) is modelled. PLC refers to the case that a receiver successfully decodes the stronger frame when collision occurs. It is shown, that PLC could potentially lead to fairness issues and higher throughput in specific cases. We study PLC in a small and large scale scenario, and show that PLC could also improve fairness in specific scenarios.

CCS CONCEPTS

•**Networks** →**Network simulations;** *Network performance analysis; Mobile networks;*

KEYWORDS

WLAN, IEEE 802.11ax, DSC, BSS Color, Physical Layer Capture, PLC

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1 INTRODUCTION

The rapid growth of the number of portable devices (i.e. smartphones, IoT wearable devices) connected to the internet, has increased the global mobile data traffic by 74% in 2015 [6]. To meet the user demands, a big share of that traffic is offloaded from the cellular onto Wi-Fi networks. The wireless local area networks (WLANs) are a cost-efficient solution that could potentially, boost the network capacity by 300% [11].

To address these demands and the new challenges that WLANs will face, a new IEEE Task Group was formed, named IEEE 802.11ax (TGax) [28]. This new task group aims at enhancing the area throughput and spectrum efficiency in dense WLAN deployments consisted of legacy and 11ax nodes. One of the requirements for 11ax nodes is that they are backward compatible with legacy WLAN nodes.

For the assessment of the techniques introduced in this standard, TGax has defined five baseline scenarios [27], namely i) Residential scenario, ii) Enterprise scenario, iii) Indoor small Basic Service Set (BSS) scenario, iv) Outdoor large BSS scenario, and v) Outdoor large BSS and Residential scenario. Each one of them consists of multiple Access Points (APs) and hundreds of Stations (STAs) and is characterized by different settings, for example different Inter Cell Distance (ICD), traffic model etc. A more detailed description of the future dense scenarios, the challenges and the use cases is presented in [3, 27].

The main features introduced in this amendment from its predecessors (IEEE 802.11n/ac) are: (a) a higher modulation scheme (1024 QAM, as an optional feature), (b) Downlink and Uplink Multi User - MIMO (DL and UL MU-MIMO, the former is supported in IEEE 802.11ac), (c) DL and UL OFDMA, and (d) spatial reuse (SR) techniques. SR schemes aim at improving spectrum efficiency and area throughput by increasing the number of concurrent transmissions in a network. This can be achieved by tuning the carrier sensing thresholds (Clear Channel Assessment - CCA) or transmit power. In this work, we study the new SR schemes that are under-consideration in [28]; Dynamic Sensitivity Control (DSC) algorithm [22] and BSS Color scheme [9], for improving the spectrum efficiency in an area. Furthermore, we exploit the capture effect along with the aforementioned schemes. It has been shown that Physical Layer Capture (PLC) in a WLAN has a significant impact on throughput and may cause fairness issues between the nodes [2, 17, 19]. In case that a stronger signal arrives during the reception of a frame, instead of losing both packets due to collision, the receiver could re-synchronize to the stronger one, as it has higher probability of surviving the collision. Thus, the system throughput could increase, whilst unfairness among the cell-edge and the rest users could aggravate. To the best of our knowledge, the effects of PLC along with a spatial reuse technique in a dense deployment have not been yet fully evaluated in the literature.

This work, presents a comprehensive simulation-based study on the capture effect in Scenario 3 [27], along with the two spatial reuse schemes (DSC and BSS Color). The ns-3 simulation tool [29] is

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used to carry out this study, whereas modifications were applied in ns-3.26 to support these functionalities, in accordance with [25, 27].

The rest of the paper is organized as follows. Section 2 presents related work and describes DSC algorithm, BSS Color scheme, and PLC. Section 3 presents the simulation scenario, while Section 4 analyses the simulation results. Section 5 concludes this paper.

2 RELATED WORK

The IEEE 802.11 family standards uses carrier sense multiple access with collision avoidance (CSMA/CA) protocol, which implies that every node senses the channel before transmitting a frame. If the channel is idle then the node can proceed to the transmission of a frame, otherwise the transmission is deferred. Furthermore, in order to minimize the probability of users transmitting at exactly the same time slot, a back-off counter is generated by every node, randomly chosen from a window (Contention Window - CW). In that way, the probability of two users initiating a transmission (after sensing the channel as idle) at a specific time slot reduces, minimizing the probability of collisions.

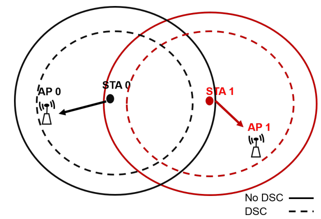
The successful reception of a frame by an IEEE 802.11 receiver, consists of three stages. First, the receiver has to successfully detect the frame's preamble and lock onto it. Following that, the receiver must successfully receive the fields included in the frame's header, and finally the payload itself in the presence of interference. Especially, the probability of a successful reception depends on the average Signal-to-Interference-plus-Noise ratio(SINR), the modulation and coding scheme (MCS), and the length of the packet.

Even though CSMA/CA minimizes the probability of collisions, it fails when the nodes cannot sense each other. This case is known as the hidden node problem. In scenarios where hidden nodes exist, collisions are inevitable. To cope with this problem the optional scheme; Request-to-Send/Clear-to-Send (RTS/CTS) was introduced in IEEE 802.11std. However, it has been shown in [4, 16] that the RTS/CTS scheme may lead to a lower network throughput or unfairness and implies only to unicast traffic.

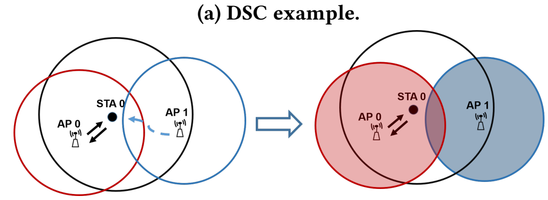
Other methods to reduce collisions include the dynamic adjustment of carrier sensing range through CCA or transmit power. The latter one can be tuned based on the interference level that neighbouring BSSs introduce, through BSS Color, which we describe in Section 2.2. An extremely low (conservative) CCA value or a very high transmit power level would eliminate the number of hidden nodes, but it would increase the number of nodes that defer their transmissions to their intended recipients (exposed nodes). The authors in [7, 33] argue that there is a balance between the number of hidden and exposed nodes in a network that maximises capacity. This balance can be achieved by adjusting the carrier sensing range.

2.1 DSC Algorithm

DSC algorithm adjusts the carrier sensing range in every station (STA), locally, without requiring any additional information to be exchanged. DSC tunes CCA thresholds based on the Received Signal Strength (RSS) value from beacons received from the associated AP. In that way, the cell-edge STAs use lower CCA thresholds than those located closer to the AP, hence increasing their probability of successful transmission by reducing the number of hidden nodes.



(a) DSC example.



(b) A simple example of BSS Color.

Figure 1: Examples of DSC and BSS Color mechanisms.

Since the nodes located close to the AP use higher CCA thresholds, they will be more aggressive in accessing the medium. To prevent the cell-edge users from starvation, DSC uses an *UpperLimit* corresponding to the maximum CCA threshold that a node can have. The STA records the beacons' RSS within a time window (*UpdatePeriod*) and calculates the average value ($\overline{RSS}$) using the moving average mechanism. The final step is to subtract from the $\overline{RSS}$ a value known as *Margin*. The value of *Margin* must be carefully set in order to keep a balance between the hidden and exposed nodes. Furthermore, DSC increments the *BeaconCount* for every consecutive missed beacon, up to *BeaconCountLimit*. If *BeaconCount* >*BeaconCountLimit* then $\overline{RSS}$ is decremented by a value (*RSSDec*).

Let us consider now, a simple example as illustrated in Figure 1a. *STA 0* and *STA 1* are within the carrier sensing range of each other, which means that they cannot transmit concurrently even if the intended receivers (*AP 0* and *AP 1*) are not in the interference range of the *STA 1* and *STA 0*, respectively. However, by adjusting CCA thresholds (i.e. with DSC) concurrent transmissions from the STAs can coexist. DSC has been studied extensively in an Enterprise [20, 23] or a Residential environment [1].

2.2 BSS Color Scheme

BSS Color is a technique used to assist a STA in identifying from which BSS a received frame originates, as illustrated in Figure 1b. In particular, the BSS Color field is carried on the Physical Layer Convergence Procedure (PLCP) header and is a 6-bit value. Its value ranges from 1 to 63, whilst a value of zero means that the BSS Color is not used. Furthermore, the *UPLINK_FLAG* is carried on the PLCP header that identifies the type of the link; a value of zero corresponds to DL traffic, whereas one is for UL. When receiving a frame, the node will check these two fields. If there is a color mismatched, then the node abandons the current reception and based on the interference level can initiate a transmission. In particular, the node will compare the RSS to a threshold, known as *OBSS_PD*. If $RSS \geq OBSS\_PD$ then it records the channel as *BUSY* and updates the Network Allocation Vector (NAV) on MAC layer.

Hence, it postpones the transmission until the end of the inter-BSS frame. If RSS <*OBSS_PD* it does not update the NAV and uses the CCA threshold to sense the channel. That is, *OBSS_PD* can increase the transmission opportunities for an 11ax node.

As we already mentioned earlier, the main objective of TGax is to enhance the system level performance and spectrum efficiency by early identification of frames originated by neighbouring/ overlapping BSSs (OBSS). Thus, *OBSS_PD* and Transmit Power can be adjusted as:

$$OBSS\_PD_{thr} = max(OBSS\_PD_{thr\_min}, min(OBSS\_PD_{thr\_max}, x)), \quad (1)$$

where $x = OBSS\_PD_{thres\_min} + (TX\_PWR_{Ref} - TX\_PWR)$, $OBSS\_PD_{thr\_min} = -82dBm$, $OBSS\_PD_{thr\_max} = -62dBm$, and $TX\_PWR_{Ref} = 21dBm$ for STAs and APs with 1 or 2 spatial streams (NSS) [26].

Moreover, if a STA selects a specific $OBSS\_PD_{thr}$ then its maximum Transmit Power is determined by the following equation:

$$TX\_PWR_{max} = TX\_PWR_{Ref} - (OBSS\_PD_{thr} - OBSS\_PD_{thr\_min}), \quad (2)$$

when $OBSS\_PD_{thr\_max} \geq OBSS\_PD_{thr} > OBSS\_PD_{thres\_min}$. The main idea of adjusting the *OBSS_PD* with the Transmit Power is to mitigate interference to OBSSs.

The authors in [15] studied BSS Color for a constant Transmit Power whilst using different $OBSS\_PD_{thr}$. Our previous work in [21] includes the evaluation of DSC and BSS Color schemes in a large-scale outdoor deployment for both UL and DL transmissions. In both studies [15, 21] DSC outperforms over BSS Color when they used individually, however the throughput gain could further increase by combining these techniques. In contrast to our previous work, here, the capture effect, frame aggregation (A-MPDU), and *OBSS_PD* are modelled.

2.3 Physical Layer Capture (PLC)

Although, DSC and BSS Color could reduce the probability of frame collisions, there might still be occasions due to the nature of the wireless medium and CSMA/CA mechanism that packets collide. Especially, in dense deployments the probability of users initiating a transmission at the same time slot increases. In the event of a collision, the receiver might still be able to successfully decode the stronger signal, even if it arrives later than the weaker signal. This event is known as PLC [24].

The works in [17, 31] show the fairness issues caused by PLC and investigate the performance of different capture models. Experimental studies of PLC are also presented in [18, 32]. The authors in [18] show the relationship between the packet arriving time and collided packet that could be successfully decoded, whereas in [32] a technique to detect and recover the collided frames is presented. In [2] the authors analyse the fairness issues among the nodes caused by PLC, and its impact on MAC protocol, whereas a simulation-based study in [8] shows that PLC favors all users, especially the cell-edge users which are more likely to detect an OBSS transmission and lock onto. The authors in [10] propose to mitigate unfairness introduced by PLC, through adjusting the MAC parameters. They show that fairness can be restored by tuning the retransmission limit, the contention window, the Transmission Opportunity (TxOP), and the Arbitration Inter-Frame Space (AIFS).

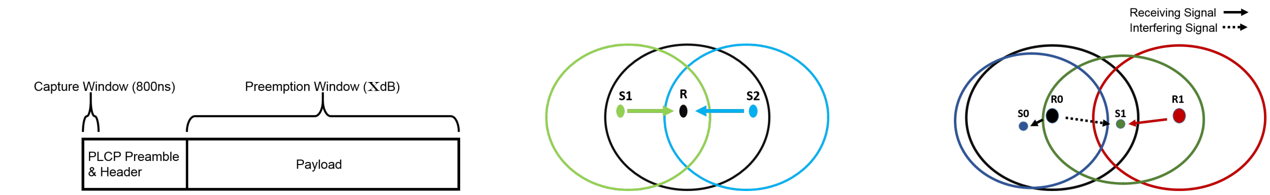
Table 1: Simulation parameters

Parameter	Value
Scenario/ Channel Model	Indoor - TGax Sce3 [27])
ICD [m] / Rings / SR	17.32 / 2 / 3
Number of APs/STAs	19/197
Wrap Around	Enabled
Frequency band [GHz]	5 (Bandwidth 20MHz)
Shadowing	Disabled
AP/STA Tx Power [dBm]	20/15 , unless otherwise specified
AP/STA antenna gain [dBi]	0/-2
Antennas (AP, STA)	1 (SISO)
Noise figure [dB]	7
PHY rate [data frames]	VHT-MCS5, unless otherwise specified
PHY rate [control frames]	VHT-MCS0
Traffic per BSS [Mbps]	100 (UDP)
RTS/CTS	Disabled
Max retransmissions	10
Packet at APP Layer [bytes]	1472, unless otherwise specified
Max A-MPDU [frames]	32 or 5.484ms, unless otherwise specified
Beacon Interval [ms]	102.4
CCA/SD, CCA/ED [dBm]	-82, -62, unless otherwise specified,
Simulation Time per run [s]	50 (40 Runs)

The capture model implemented in this work follows the procedure descibed in [25]. In particular, a receiver captures the strongest signal detected within a capture window. This capture window has a duration of 800ns and it starts at the first arrival frame with RSS above the Rx Sensitivity. At the end of the capture window, the receiver locks onto the strongest signal whose preamble is to be decoded. If a frame arrives after the end of the capture window and within the preamble duration of the strongest signal, it is considered as interference. Following a successful reception of the preamble, the capture phase starts again. This time, the window, a.k.a. Pre-emption Window, has duration equal to the duration of the frame whose preamble has been successfully decoded. If a new frame arrives during the Pre-emption Window, the receiver will lock onto it, if its RSS is at least XdB above the RSS of the current reception ($RSS_{new} \geq (RSS_{cur} + X)$). X is known as the capture threshold, and commonly a value of 10 dB is used. Then, the current reception terminates, the receiver captures the newly arrived frame, and the capture procedure starts again. The starting time and duration of the capture and pre-emption window with respect to a receiving frame, are illustrated in Figure 2a.

3 EXPERIMENTAL SETUP

To test fairness and throughput performance of WLAN with the effect of capture model, we create three scenarios: two small-scale ad-hoc topologies, depicted in Figures 2b and 2c and one large-scale, illustrated in Figure 3. In the small-scale scenarios, each circle represents the carrier sensing range of each node. In the former case (*Case 1*), there is only one receiver (R) and two hidden senders (S1, S2) which are equidistant from the receiver. Whilst, in the latter test case (*Case 2*), there are two senders (R0, R1) hidden from each other, transmitting traffic destined to S0 and S1, respectively. S1



(a) Duration of capture and pre-emption window. (b) Frames to the same receiver. (c) Frames to different receivers.

Figure 2: Capture and Pre-emption Window in the presence of hidden nodes.

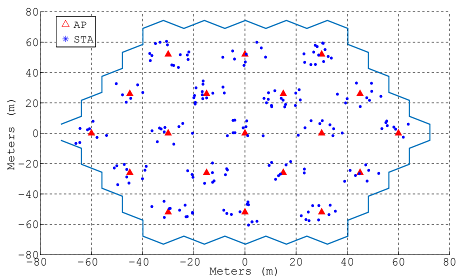


Figure 3: Simulation Scenario (Spatial Reuse 3, Rings 2).

node is an exposed node, since both R0 and R1 are within its carrier sensing range. That means, S1 could lock to a frame originated by R0 or R1, and could transmit a frame when both R0 and R1 do not transmit any frame. Moreover, S1 is placed closer to R1 than to R0, such that $RSS\_R1 = RSS\_R0 + 0.11$ when both R0 and R1 transmit at the same power level. In both experiments. the senders are hidden from each other, hence can transmit simultaneously, whereas the capture threshold is set equal to 0.1 dB. We, also consider both Broadcast and Unicast traffic in order to study the impact of PLC on MAC layer.

We then evaluate the performance of DSC and BSS Color in a dense deployment consisted only of 11ax nodes (nodes that support DSC or BSS Color). The APs are placed in fixed location, whilst STAs randomly placed in a reference area, as illustrated in Figure 3. In particular, this reflects to Scenario 3 from the list of TGax baseline scenarios [27], an indoor small deployment. Moreover, we apply a wrap-around technique [12], so that BSSs located at the outer rings experience a similar interference as those at the inner rings. The original hexagonal network is extended to a cluster of 6 virtual copies of the original layout. These virtual copies are placed around the original network. In that way, a small fraction of a larger deployment can be studied instead of the entire large network. If wrap-around is not used, then we can assess performance only of the simulated layout and not the entire network. We also assume that all nodes establish the Block Ack Agreement instantly and disassociation do not occur (*Missed Beacons* is set to infinite). The simulation parameters used in this study are listed in Table 1.

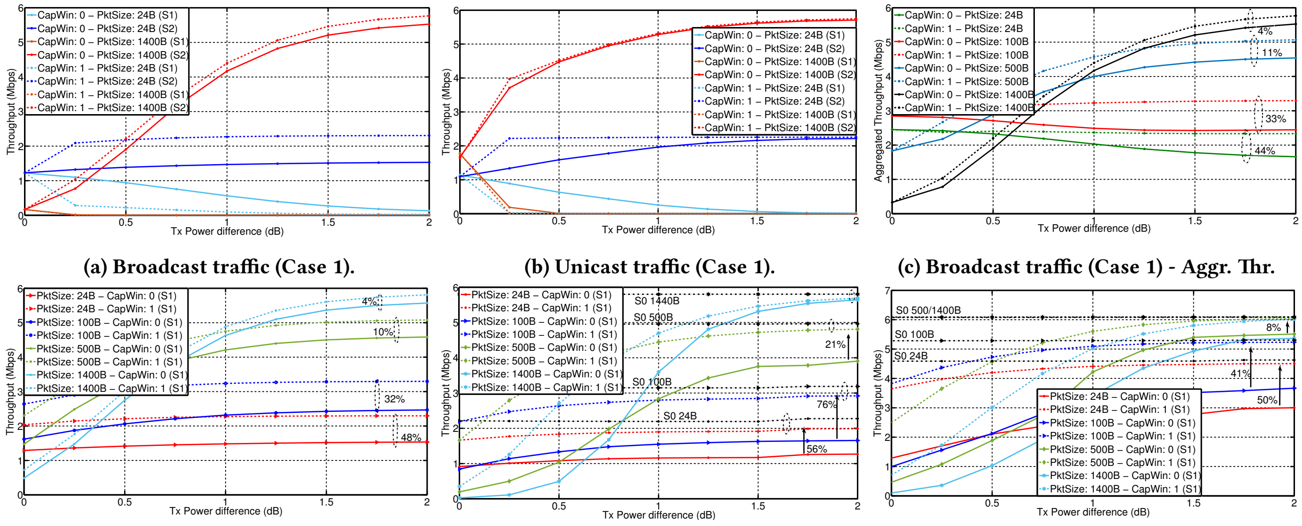
DSC is also implemented following [22] with the addition of two *Margin* values for *CCA/ED* and *RxSensitivity* (CCA/SD) as in [21]. On the other hand, we assume no color collisions and the Color id is carried on the PLCP header without increasing its transmission time, since we used 802.11ac physical layer. Specifically, it is included in the HE-SIG-A1 field, that means it is the first field following the legacy portion of the preamble. In ns-3 the whole preamble is for now considered as a standalone sub-frame. However, we further separated the preamble reception based on the fields included in it. In that way, a node may identify a color mismatched earlier instead of waiting until the end of the whole preamble. Furthermore, if a field is not successfully detected, then a node sets CCA threshold or the channel as *BUSY* according to PHY receive state machine flowchart [13, 14]. Lastly, once receivers successfully decode a preamble, they lock onto that transmission until the last A-MPDU frame, which also means that Pre-emption window's duration extends until the end of the last A-MPDU frame.

4 SIMULATION RESULTS

This section presents the performance evaluation of a) PLC, b) DSC, and c) BSS Color schemes in the aforementioned small and large-scale scenarios, in terms of fairness, average user and aggregated throughput. We define fairness for the small-scale scenarios, as the user throughput ratio, whereas in the large-scale scenario can be observed from the gradient of the cumulative distribution function (cdf) lines. The aggregated throughput in the large-scale deployment is per channel (20MHz) and normalised per km^2 due to the use of wrap-around.

4.1 PLC Impact

First, we study the impact of PLC in scenarios *Case 1* and *Case 2* with data rate VHT-MCS0. Figures 4a to 4c present the impact of PLC in terms of user and aggregated throughput for broadcast and unicast traffic for *Case 1*, depicted in Figure 2b. The x-axis represents the difference of the Transmit Powers between S2 and S1; $TxPwr\_S2 - TxPwr\_S1$. As S2 increases its Transmit Power, fairness deteriorates since S2 throughput improves whereas that of S1 reduces. We also observe that fairness between S1 and S2 further deteriorates with PLC (*CapWin: 1*), especially for small packet sizes. Smaller packet sizes have higher probability of successful reception with or without PLC. Thus, when a receiver locks onto a small packet, the transmission will be most probably successful. However, this is not the case for large packets as they have lower probability of successful transmission. This is the main reason, PLC has more impact on small smaller packets in terms of throughput and fairness. Unfairness is even higher in unicast traffic due to MAC retransmissions and Contention Window size. We only present the aggregated throughput for broadcast traffic, as for unicast traffic *throughput gain* $\approx 1\%$ for PLC. A similar behaviour is also observed for VHT-MCS3, but for higher SINR, especially for packet sizes of



(a) Broadcast traffic (Case 1). **(b) Unicast traffic (Case 1).** **(c) Broadcast traffic (Case 1) - Aggr. Thr.**

(d) Broadcast traffic (Case 2). **(e) Unicast traffic (Case 2).** **(f) Unicast traffic (Case 2) - A-MPDU: 5.**

Figure 4: Impact of PLC in terms of throughput and fairness.

500 and 1400 bytes ($SINR \approx 8$ and 10, respectively). However, due to space limitation we do not present these results.

Figures 4d to 4f depict the results obtained for *Case 2*, illustrated in Figure 2c. In that case, fairness improves since throughput of S1 approximates this of S0 when PLC is modelled. The aggregated throughput gain is significant higher than in *Case 1*, as PLC increases the number of successful concurrent transmissions. That is, PLC can improve throughput and fairness, especially for the cell-edge users in specific scenarios.

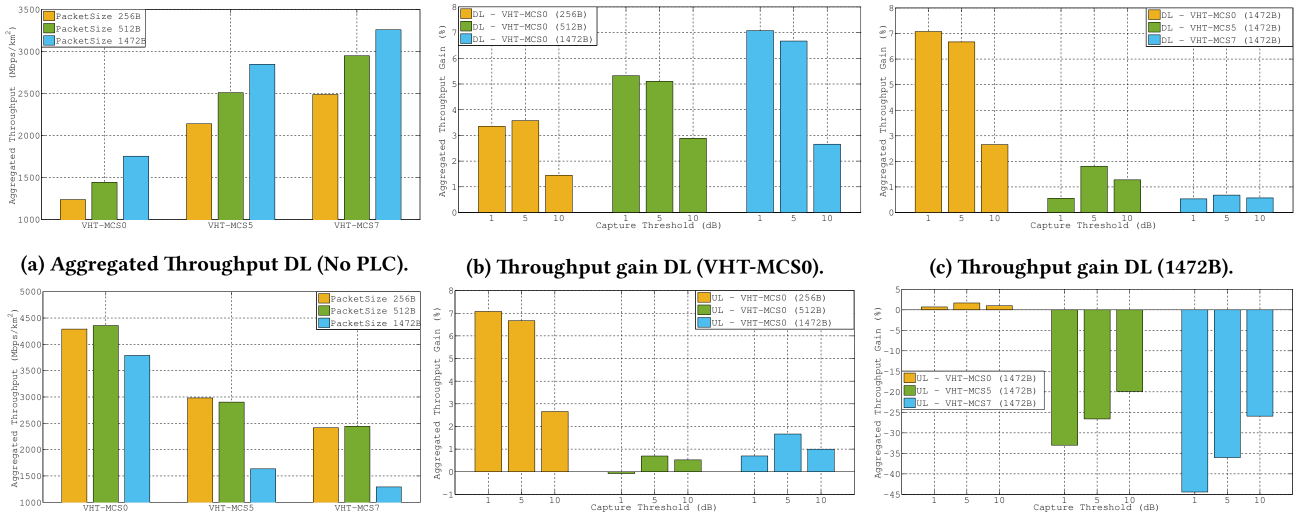
We now study the impact of PLC in SC3 [27] presented in Figure 3 for different packet size, data rate, capture threshold, and transmission link; DL only and UL only. Since the signal strength difference required for PLC depends on MCS and there are techniques to tune PLC properties [5, 30], we use three different capture thresholds, namely: 1, 5, and 10 dB [8, 31, 32].

Figure 5 illustrates the aggregated and gain throughput of PLC against various data rates and packet sizes. Figure 5a presents the impact of different data rates when capture threshold is set to an extremely large value (PLC is disabled). As we expected, throughput improves as higher data rate is used, even for large frame sizes. That means SINR is sufficient for successful transmissions in that specific case. Note that the distance between two co-channel BSSs is approximately 30m due to Spatial Reuse 3. In Figure 5b the throughout gain of various capture thresholds is depicted. We can observe that throughput gain further improves as the frame size increases. This is due to the combination of low data rate which is more robust to interference and the duration of PLC windows. Especially, the ratio of PLC windows and the time window between them, that PLC is not used (No PLC). As the frame size increases, the ratio of PLC and No PLC window increases, which means that the probability of a frame arriving within the PLC windows increases. Two important outcomes can be derived from Figure 5c. First, the gain decreases as data rate increases, since higher data rates require higher SINRs for successful transmissions. Second, as data rate increases, a higher capture threshold results in a higher throughput gain.

On the other hand, in UL case, high data rates and large packet sizes result in a poor performance, Figure 5d, since they are more susceptible to low SINR. The number of nodes, now, competing to grant access to channel is 10x times than in DL case, increasing interference. This is also, the main reason that throughput gain is higher for smaller frame sizes, as illustrated in Figure 5e.

A negative throughput gain can be observed in Figure 5f for large frame sizes and high data rates. After, closely analysing that behaviour we found out that the negative gain is due to max Ampdu number. By restricting the number of Ampdu to 1 frame for VHT-MCS7 and setting the capture threshold to 5, we observed a positive throughput gain. Let us assume a STA that initiates a transmission (*Tx0*) to AP. If the packet preamble is successfully decoded by all STAs within the BSS then they will defer their transmissions until the end of the ongoing transmission. In case that at least one STA fails to decode preamble, then it might initiate a transmission (*Tx1*) after a specific number of time slots, depending on the interference level and *CCA/ED* threshold. *Tx1* may interfere with *Tx0* depending on the transmission duration of the latter one. Now, the AP will lock onto the newly arrived frame based on the capture threshold. In case that capture threshold is set to a small value, SINR might not be sufficient enough to successfully decode the newly arrived packet or even its preamble. This could result both STAs to transmit Block-Ack requests or even retransmit all their frames even though some of them might have been correctly received. If PLC is disabled, then the AP would acknowledge the first STA and inform it about the number of successfully received frames, reducing the overhead of retransmissions.

The positive throughput gain of PLC in DL case is mainly due to the fact that STAs drop frames transmitted by OBSSs when a stronger signal arrives, as in *Case 2*. Whilst, in UL case, there are multiple senders that could be hidden to each other, transmitting



(a) Aggregated Throughput DL (No PLC). (b) Throughput gain DL (VHT-MCS0). (c) Throughput gain DL (1472B).

(d) Aggregated Throughput UL (No PLC). (e) Throughput gain UL (VHT-MCS0). (f) Throughput gain UL (1472B).

Figure 5: Impact of PLC in terms of aggregated and gain throughput in Scenario 3.

to the same receiver which could result to a negative throughput gain in specific cases. In such cases, appropriate CCA thresholds could eliminate the concurrent transmissions within the same BSS.

4.2 DSC Evaluation

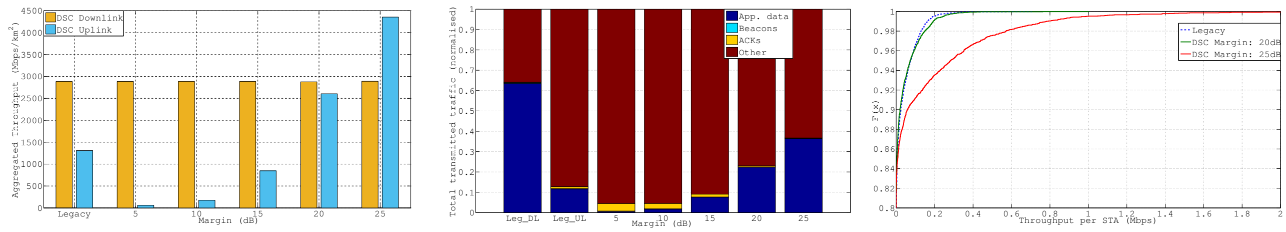
We evaluate DSC for 5 different *Margin* values, whereas *UpperLimit* is set to *-40* for all cases. The *Margin* values are depicted in Figure 6a, while a capture threshold of 10 dB is used. In DL case, only *CCA/SD* is tuned whereas a *Margin* value of 20 is used for *CCA/ED*. In UL, a similar approach is followed but this time, *CCA/ED* is tuned whilst a *Margin* value of 5 is used for *CCA/SD*. We observe in this figure, that different values of *Margin* have negligible impact on throughput in DL case. The throughput gain in that case is marginal ($\leq 1\%$) due to PLC. Specifically, even if a node locks onto a signal originated by an OBSS, it may abandon this reception if detects a stronger signal which was possibly transmitted by its associated AP, unless that frame arrives between Capture and Pre-emption window. Since the duration between Capture and Pre-emption window is small compared to the total duration of those windows, the probability of receiving a stronger frame within that duration is extremely small, hence the low throughput gain. A potential higher throughput gain could be observed though, in a bi-directional case when a STA has also frames to transmit. In UL case, as *Margin* increases, carrier sensing range also expands, increasing the probability of successful transmissions, eliminating the concurrent transmissions of STAs within the same BSS. However, an extremely low *Margin* results in a negative throughput gain compared to Legacy one, due to the hidden node problem.

Figure 6b depicts the impact of *Margin* on overheads. The first bar represents the DL case, whereas *Other* the retransmitted data. We only present one bar for DL, since the results do not significantly vary for different *Margin* values. In UL case, a high percentage of ACKs transmissions and retransmissions for small *Margin* can be observed due to the extremely small carrier sensing range. One important outcome, is the packet delivery ratio (PDR) that can be derived from this figure. A value of 20 offers an almost two-fold better PDR than the legacy does, whereas when $Margin = 25$, PDR further improves.

Figure 6c presents the average throughput per STA in UL case. Three important conclusions can be drawn from that figure. First, throughput has been generated by less than 20% of the total STAs. Second, the throughput gain of $Margin = 20$ is due to a small fraction of the STAs ($\approx 3\%$) that takes advantage of the smaller carrier sensing range. They are located close to the APs as their signal should be strong enough to trigger PLC and also survive collisions. Lastly, a value of 25 favours a bigger portion of the STAs, not only those located very close to an AP. However, we could argue that fairness deteriorates for these STAs due to the gentle slope. After closely analysing the results, a *Margin* value of 25 for *CCA/ED* seems more suitable for the specific scenario, whereas a small one for *CCA/SD* could potentially increase the transmission opportunities for a STA assuming low-mobility in a bi-directional (DL and UL) scenario.

4.3 BSS Color Evaluation

We evaluate BSS Color for different $OBSS\_PD_{thr}$ and transmit power levels, while a capture threshold of 10 dB is used. In particular, we set a specific transmit power for a node, while $OBSS\_PD_{thr}$ is adjusted using Eq. 1. Figure 7a illustrates BSS Color performance in terms of throughput for DL and UL cases. The x-axis represents the transmit power for APs and STAs, $(TxPwr\_AP, TxPwr\_STA)$. For example, when $(TxPwr\_AP, TxPwr\_STA) = (20, 15)$, then the threshold is $(OBSS\_PD^{AP}_{thr}, OBSS\_PD^{STA}_{thr}) = (-81, -76)$. In DL case, we observe that for the $(20, 15)$ and $(17, 12)$ cases throughput slightly decreases compared to *Legacy*, whereas a further reduce in transmit power results in extremely low throughput. First, reducing transmit power might improve spatial reuse by increasing the number of concurrent transmissions, which could lead to higher interference



(a) Aggregated Throughput. **(b) Impact of DSC on overheads.** **(c) Ecdf for UL transmissions.**

Figure 6: DSC metrics.

level. In addition, BSS Color increases the transmission opportunities which could result in low SINR that is not sufficient enough for successful transmissions. A similar behaviour is observed in UL case. However, this time throughput decreases more rapidly as transmit level reduces. In addition to high interference level from OBSSs, in UL case, due to the high *CCA*/*ED* there are hidden nodes within the same BSS that could further increase the probability of collisions or decrease SINR.

Figure 7b presents the impact of BSS Color on overheads. The four left-hand bars stand for DL case, whereas the rest four for UL. Two outcomes can be derived from this figure. First, PDR decreases with the transmit power. Second, as transmit power reduces, the *ACK* portion increases, indicating the high number of retransmissions. Especially, in UL case, the high number of acknowledgements could be due to PLC as described in Section 4.1.

Figure 7c depicts the average throughput per STA in UL case. Even though BSS Color increases the transmission opportunities, especially for the cell-edge users that could lock onto a frame originated from an OBSS, we observe that the throughput of these nodes dramatically drops. Their performance becomes even worse as $OBSS\_PD_{thr}$ increases. This is due to lower transmit power, which could reduce interference level to OBSSs but it might increase the number of hidden nodes within the BSS.

To cope with the hidden node problem, BSS Color is now applied along with DSC. DSC reduces the probability of concurrent transmissions within a BSS through *CCA/ED* and the probability of a node locking onto a preamble originated by an OBSSs through *CCA/SD*. On the other hand, the main advantage of BSS Color is blocking the reception of OBSS frames and increasing transmission opportunities through *OBSS_PD* and *CCA/ED*. The *Margin* values used in that case are; 5 for *CCS/SD* and 20, 25 for *CCA/ED*.

Figure 8a illustrates the performance of BSS Color along with DSC algorithm in DL transmissions. We present the results when $Margin = 20$ for *CCA/ED* since the results for a value of 25 dB do not vary significantly. We observe that DSC has a negligible impact in that case. This is because, DSC is only applied on STAs, which means that it does not block APs from transmitting. The small deviation in throughput gain observed in that case, is due to the expanded carrier sensing range for the STAs and the small share of the traffic transmitted in the UL link (Block-Acks).

On the other hand, in UL case, as most of the traffic is transmitted from STAs, DSC highly affects the system performance as depicted in Figure 8a. Two important outcomes can be drawn from this figure. First, the great impact of adjusting the carrier sensing range compared to the case where only BSS Color is used. Second, a *Margin* value of 20 dB achieves higher throughput gain than 25 dB, compared to the case where only DSC is applied with the same values. This is because BSS Color blocks all OBSS frames, whilst DSC does not and due to transmission opportunities through *OBSS_PD* and *CCA/ED*. A very low *CCA/ED* will force a STA to defer its transmission, even if the received signal of an OBSS frame is below *OBSS_PD*. This is the main reason that throughput gain is approx. 10% and 1% for a value of 20 and 25 dB, respectively, compared to DSC.

After analysing the results, we argue that DSC outperforms over BSS Color, whereas by combing these schemes, a higher throughput gain can be observed. The poor performance of BSS Color could be due to PLC in addition to small ICD and low SINR for the data rate used in this study.

5 CONCLUSION

In this paper, we investigated the performance of DSC, BSS Color, and a combination of these schemes when Physical Layer Capture (PLC) is modelled. First, we studied PLC in a small and large-scale scenario. We observed the fairness issues caused by PLC reported in previous works, but we also presented a case where PLC improves fairness. Following that, we evaluated the performance of DSC and BSS Color in a large deployment for both downlink and uplink transmissions. We showed that, by utilizing DSC, the system throughput enhances, whereas we explicitly analysed the reasons of BSS Color's poor performance in the specific scenario. By jointly applying the aforementioned schemes, we observed that network throughput can be further increased. Directions for future study include the study of DSC and BSS Color in different scenarios along with a DSC scheme operating at APs to overcome the high interference from OBSSs.

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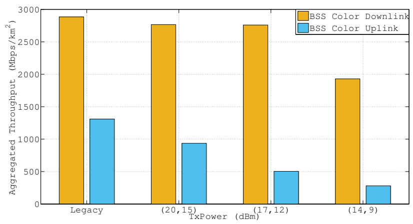
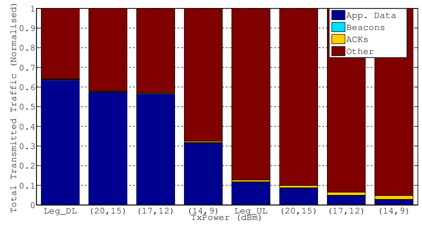
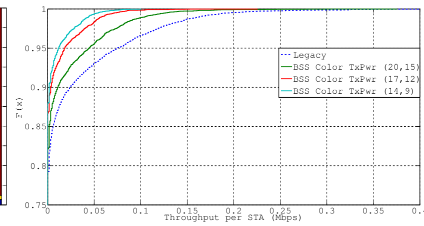


(a) Aggregated Throughput.

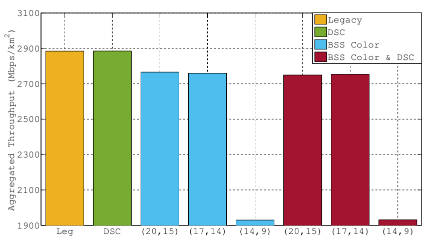


(b) Impact of BSS Color on overheads.

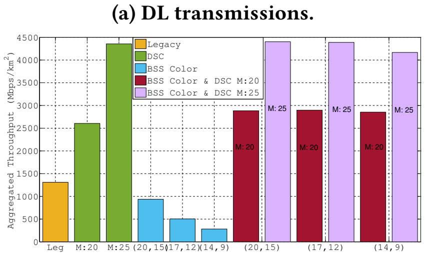


(c) Ecdf for UL transmissions.

Figure 7: BSS Color metrics.



(a) DL transmissions.



(b) UL transmissions.

Figure 8: BSS Color along with DSC.

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