

Evaluation of RTOT algorithm: a first implementation of OBSS_PD-based SR method for IEEE 802.11ax

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Abstract—The main goal of the IEEE 802.11ax project is to improve the network efficiency of IEEE 802.11 systems in dense deployments. There are currently several methods under consideration in the IEEE 802.11ax task group to achieve the aforementioned goal, including Multi-User Multiple Input Multiple Output (MU-MIMO), Multiple Packet Data Unit-aggregation, channel bonding, in addition to several Spatial Reuse (SR) improvements strategies.

In this paper, we focus on the SR improvements methods and more specifically on one of the proposed solution at IEEE to improve SR for 802.11ax: Overlap Basic Service Set Physical Detection (OBSS_PD)-based SR. This solution combines adjusting the power transmission and Carrier Sense Threshold (CST) in order to increase the number of successful concurrent transmissions in dense networks. In this article, we propose and evaluate the RSSI To OBSS Threshold (RTOT) algorithm which is, to the best of our knowledge, the first algorithm to implement OBSS_PD-based SR technique. RTOT uses the beacon Received Signal Strength Indicator (RSSI) to dynamically compute the CST, and derive afterwards the transmission power to use.

We evaluate RTOT algorithm by simulation in a dense scenario. We show that the overall system throughput can be improved up to 80 % compared to IEEE 802.11 legacy networks. We highlight that the overall throughput improvement comes at the expense of per-station throughput degradation, and thus the fairness among stations is severely compromised. A trade-off must be considered between maximizing the overall throughput and maintaining an acceptable per-station throughput.

I. INTRODUCTION

With an installed base of more than 7 billions devices, IEEE 802.11 Wireless Local Area Network (WLAN) technologies' success is indisputable. WLAN Stations (STAs) and Access Points (APs) have been massively deployed in the recent years due to their convenience for users, their ease of installation and their cost efficiency [1]. WLAN has become ubiquitous in our everyday life and our constant need to be always connected has lead to an increased densification of the network. The IEEE 802.11 Task Group ax (TGax) is currently defining a revision to the IEEE 802.11 standard to address the densification main consequence, i.e., a massive increase of the interference leading to lower overall throughput. The goals of IEEE 802.11ax are to not only improve the overall system throughput but also the per-station throughput by a factor of four [2].

In this article, we focus on SR improvement techniques, one of the most promising solution to deal with the densification problem. SR improvement aims to increase the number of successful concurrent transmissions in the network. As described in [3] and [4], there are two main methods to improve SR: Carrier Sense Threshold (CST) tuning and Transmit Power Control (TPC).

CST is used by the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to manage the access to the channel by sensing it prior to transmission. A packet is transmitted only if the channel is found to be *idle*. On the other hand, if the channel is found to be *busy*, the transmission is deferred. The channel is considered as *idle* if the measured energy level on the channel is below the CST. In the IEEE standard, the CST value is fixed and set to a low value (e.g., -76 dBm for 802.11ac 80 MHz) [5]. The smaller the CST value is, the smaller is the amount of energy needed to assert the channel to be *busy*, i.e., the larger is the carrier sensing range. CST tuning aims to adapt the CST to modify the carrier sensing range. By increasing whenever possible the CST value, the carrier sensing range is reduced, allowing more concurrent transmissions.

TPC allows STAs to change their transmission power with the purpose to maximize the system performances. TPC impacts SR in two ways. On one hand, the transmission power defines de-facto the transmission range of a node and thus influences the CSMA/CA protocol. On the other hand, transmitting with higher power can unnecessarily silence concurrent transmissions and/or generate too much interference.

Combining both TPC and CST tuning allows to obtain maximal SR improvement. TPC diminishes the amount of nodes impacted by a given transmission by reducing the transmission power, while CST tuning gives more transmission opportunities by shrinking the carrier sensing range. The main challenge is to reduce the transmission power to the adequate level guaranteeing the correct reception of the transmitted frame by the intended receiver while keeping a CST large enough in order to consider the channel as busy if the transmission interference level is too high to allow multiple transmissions .

OBSS_PD-based SR, proposed at TGax, uses both CST tuning and TPC [6]. OBSS_PD-based SR defines the relationship between the CST and the associated transmission power to use by a STA for its transmissions. However, OBSS_PD-based SR does not describe how to obtain the CST value or the transmission power. In this article, we propose RSSI To OBSSPD Threshold (RTOT) algorithm which computes first the CST by using the beacon Received Signal Strength Indicator (RSSI) value. Once computed, the CST value is fed to OBSS_PD-based SR to derive the transmission power to use. We evaluate RTOT performance in a dense scenario proposed in TGax simulation scenarios document [7].

The major contributions of this paper are summarized as follows:

- (i) We propose RTOT, the first algorithm to the best of our knowledge that implements OBSS_PD-based SR. RTOT shows the benefits of using OBSS_PD-based SR while remaining simple enough to not add any additional overhead or to impose any hardware/standard modification.
- (ii) We highlight the existing trade-off between increasing overall system throughput improvements and fairness among STAs when using SR improvement techniques in dense environment.
- (iii) We provide recommendations for future OBSS_PD-based SR algorithms design.

The rest of the paper is organized as follows: Section II presents SR related work. Section III outlines the OBSS_PD-based SR solution. Section IV describes the RTOT algorithm, and Section V presents the scenario and the parameters used to study RTOT. Section VI discusses the results while finally, Section VII concludes the paper and propose some potential extensions to our work.

II. RELATED WORK

A large number of studies have been conducted in order to investigate the CST tuning effects on SR (throughput and capacity) for IEEE 802.11 network. Zhu et al. reveal the impact of CST tuning for throughput enhancements [8]. The authors show that changing CST values leads to significant throughput increase but never mention how to compute and adjust the CST values dynamically. The authors in [9] and [10] provide a comprehensive study on CST tuning by analyzing numerically its impact on interference and SINR and how it could improve SR. However, the authors' solutions rely both on introducing new signaling and thus additional overhead in order to dynamically adapt CST. More recently, Dynamic Sensitivity Control (DSC) was proposed at TGax [11]. This solution allows to dynamically compute CST by using beacon RSSI. This approach is studied in a number of IEEE contributions (see [12], [13], [14]). DSC shows huge gain regarding throughput. However, DSC only relies on CST tuning and does not exploit the additional benefits of TPC.

The use of TPC in SR context has been studied in [15], [16] and [17] where the authors introduce respectively PCMA, PCDC and POWMAC protocols. These three protocols work

by adapting the transmission power in order to not disrupt ongoing transmission by letting the receiver of the transmission advertise the level of interference it can support. However, all these three protocols do not address the overhead due to the advertisement of the interference values, the impact of the CST on their protocol, and the relationship between the transmission power and the CST to obtain the optimal network performance.

Not so many studies have been conducted combining the transmit power and CST. Roslan et al. present a new method to tune both transmission power and CST [18]. While the authors show big improvements regarding to throughput and fairness, the usage of a bloom filter to determine if a frame is coming from an inter or an intra BSS imposes changes to every device. Yang et al. propose an algorithm to determine both the transmit power and the carrier sense of a node [19]. However, this solution works by advertising the position of each STA in a HELLO message which adds signaling overhead and requires to implement a localization functionality on every STA and AP.

III. OBSS_PD-BASED SR

In dense deployments, due to the limited number of available channels, several Basic Service Sets (BSS), i.e., a single AP with all its associated STAs are going to operate on the same channel and thus leading to Overlapping BSS (OBSS). OBSS_PD-based SR, proposed in IEEE TGax, works by using CST tuning and TPC jointly in order to cope with the OBSS situation. For CST tuning, two different thresholds are used: the legacy CST and the newly defined $OBSS_PD_{Thr}$. The legacy CST is used for for intra-BSS frames i.e. frames coming from the BSS on which the STA is associated, while $OBSS_PD_{Thr}$ is employed for inter-BSS frame, i.e., frames coming from another BSS. The legacy CST is fixed as defined in 802.11 standard while $OBSS_PD_{Thr}$ is adjustable and should be larger than the legacy CST to allow further spatial reuse. In order to determine if a frame is intra or inter-BSS, BSS coloring is used [20]. Each BSS node inserts a new field called BSS color in the preamble of every 802.11 frames. Each BSS color field is defined by the AP of the BSS and each BSS has a different color, allowing a STA to decode the preamble and determine from which BSS the frame is coming from.

Figure 1 depicts the principle of using OBSS_PD-based SR with two BSSs. BSS1 is made of AP1, STA1 and STA2 while BSS2 is made of AP2 and STA3. BSS1 and BSS2 operate on the same channel so they form an OBSS. $OBSS_PD_{Thr}$ is larger than the legacy CST resulting in a smaller carrier sensing range for frames coming from an inter-BSS. Let's consider the case where the three STAs want to simultaneously transmit to their respective APs and that STA1 is the first one to gain channel access. As the STA1 frame is an intra-BSS frame for STA2, STA2 uses the legacy CST to assert if the channel is *busy* or *idle*. As STA1 is inside STA2 legacy carrier sensing range, STA2 defers its transmission to avoid collisions. On the other hand, STA3 uses $OBSS_PD_{Thr}$ as STA1 frame is an inter-BSS and thus, STA3 asserts the channel to be *idle* as

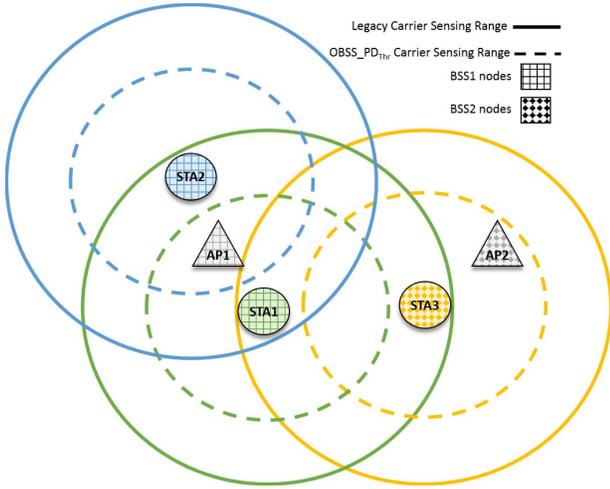


Figure 1: An illustration of OBSS_PD-based SR in action

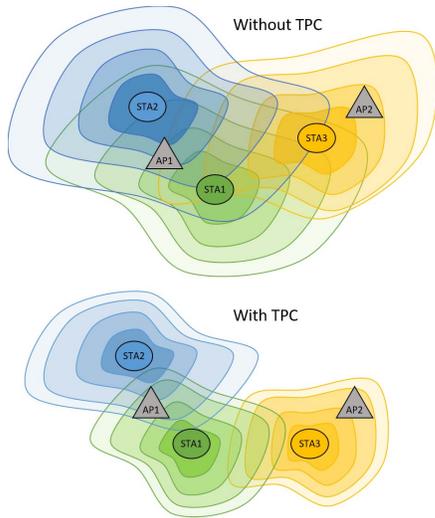
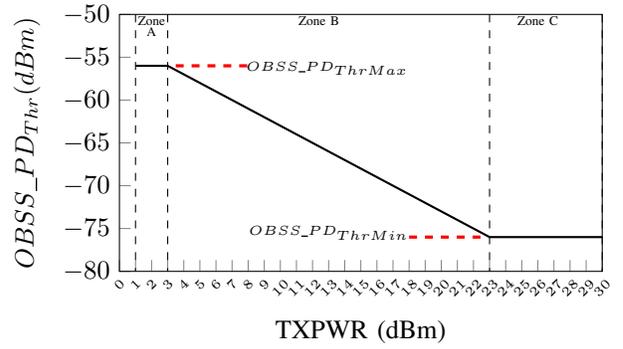


Figure 2: Benefits of using TPC in case of OBSS. The colored area represents the strength of the power received by a receiver. The stronger the color, the larger the power received.

STA1 is outside of STA3 $OBSS_PD_{Thr}$ carrier sensing range. As a result, STA1 and STA3 may transmit successfully at the same time if the level of interference generated by each STA on the other is low enough to allow successful decoding of STA1 and STA3 frames by their respective AP.

For allowing even greater SR, TPC is used. The transmission power ($TXPWR$) is decreased in order to minimize the OBSS transmissions' impact on other OBSSs. Figure 2 illustrates the principle of using TPC in the topology described in Figure 1. Without TPC, all STAs transmit at their maximum configured power. If STA1 transmits to AP1, STA2 and STA3 experience large interferences. With TPC, STAs reduce dynamically their transmission power. For example, STA1 transmission power is going to be reduced and thus, STA2 and STA3 receive lower level of interference. The main challenge for TPC is to reduce the power to an adequate level in order to allow a successful transmission (i.e. generate a high enough SINR at the receiver side) while reducing the impact of the

Figure 3: Relationship between $TXPWR$ and $OBSS_PD_{Thr}$ for a 80 MHz bandwidth

resulting interference.

OBSS_PD-based SR defines a proportional relationship between $OBSS_PD_{Thr}$ and $TXPWR$. $OBSS_PD_{Thr}$ is computed using (1).

$$OBSS_PD_{Thr} = \max \begin{cases} OBSS_PD_{ThrMin} \\ \min \begin{cases} OBSS_PD_{ThrMax} \\ OBSS_PD_{ThrMin} + (TXPWR_{ref} - TXPWR) \end{cases} \end{cases} \quad (1)$$

where $OBSS_PD_{ThrMin}$ and $OBSS_PD_{ThrMax}$ are the respectively minimum and maximum possible values for $OBSS_PD_{Thr}$. $TXPWR_{ref}$ is the reference transmission power and $TXPWR$ is the actual transmission power. $TXPWR_{ref}$, $OBSS_PD_{ThrMin}$, and $OBSS_PD_{ThrMax}$ have fixed values defined in the OBSS_PD-based SR document [6] for a 20 MHz bandwidth (see table I) and equations are provided to calculate them for different bandwidths. In this paper, we evaluate the performance of OBSS_PD-based SR using a 80 MHz bandwidth as recommended in the simulation scenarios defined by TGax [7]. Thus, values used in the remaining of the article are the ones shown in Table I for a 80 MHz bandwidth. Finally, $TXPWR$ is computed using (2).

$$TXPWR = OBSS_PD_{ThrMin} + TXPWR_{Ref} - OBSS_PD_{Thr} \quad (2)$$

Resolution of (1) by varying the power between 1 dBm and 30 dBm for a 80 MHz bandwidth is shown in Figure 3. Three zones, A, B and C are noticeable as highlighted on Figure 3. Zone A (between 1 dBm and 3 dBm) corresponds to the case where the $TXPWR$ used to transmit has its minimum value and the $OBSS_PD_{Thr}$ its maximum value ($OBSS_PD_{ThrMax}$). Transmitting with a lower power reduces interference while having a large $OBSS_PD_{Thr}$ reduces the sensing range of the

Table I: OBSS_PD-based SR default values

Bandwidth	$TXPWR$	$OBSS_PD_{ThrMin}$	$OBSS_PD_{ThrMax}$
20 MHz	23 dBm	-82 dBm	-62 dBm
80 MHz	23 dBm	-76 dBm	-56 dBm

inter-BSS frame and thus increases concurrent transmissions. This zone produces the maximum increase of SR, and is typically used when the distance between the STA and the AP is small. Zone B (over 3 dBm and less than 23 dBm) is the adaptation zone, where the $TXPWR$ and the $OBSS_PD_{Thr}$ are adapted proportionally to guarantee the best possible SR. The larger is the transmission power, the smaller is the $OBSS_PD_{Thr}$. Finally, Zone C (after 23 dBm) corresponds to the case where the $TXPWR$ used to transmit is at the maximum value and the $OBSS_PD_{Thr}$ is set to its minimum value ($OBSS_PD_{ThrMin}$). An STA far away from its AP is going to use this configuration as it needs to transmit with high power in order to be successfully decoded by its AP. Moreover, $OBSS_PD_{Thr}$ is set to its minimum value as in a dense environment, being far away from the AP means potentially a higher chance to be close to another OBSS and thus the need for the STA to take into account interference from other OBSSs. This zone corresponds to the minimum SR case.

IV. RTOT ALGORITHM

As described in Section III, the $OBSS_PD$ -based SR solution describes the relationship between $OBSS_PD_{Thr}$ and $TXPWR$, i.e., having one of these values allows us to compute the other. However, how to obtain these values and more specifically which one to use to derive the other is not addressed by $OBSS_PD$ -based SR as it is considered up to the implementer/vendor. Whichever $OBSS_PD_{Thr}$ or $TXPWR$ values are obtained first must express the relative distance to the AP in order to dynamically react to mobility/link quality, and provide enough diversity in order to fully take advantage of the benefits offered by the three $OBSS_PD$ -based SR zones. Therefore, in this paper, we propose RTOT algorithm which operates by using beacon RSSI to compute $OBSS_PD_{Thr}$ before to derive afterwards the $TXPWR$ thanks to $OBSS_PD$ -based SR. Beacon RSSI is a good candidate to express the relative distance to the AP as it captures the received signal strength from the AP. The closer a STA from an AP is, the larger the beacon RSSI is and vice versa.

Algorithm 1 presents the pseudocode of the RTOT algorithm. The following notations are used:

- $Beacon_{RSSI}$: the RSSI of the beacon transmitted by the AP on which the STA is associated to.
- M : the margin, i.e., the value subtracted from the beacon RSSI to turn it into an $OBSS_PD_{Thr}$ value.
- $TXPWR_{Min}$: the minimum transmission power allowed for a STA.
- $TXPWR_{Max}$: the maximum transmission power for a STA (i.e., the $TXPWR$ set for a given STA as TPC can only decrease $TXPWR$).

The goal of RTOT algorithm is to provide a large $OBSS_PD_{Thr}$ and a small $TXPWR$ value when the STA is close to its AP (i.e., when the beacon RSSI is having a large value) assuming that a STA close to its AP can seek for the maximum SR. The further away is the STA from its AP, the smaller should be the $OBSS_PD_{Thr}$ value and the higher should be

Input: $Beacon_{RSSI}, M$
Output: $OBSS_PD_{Thr}, TXPWR$
 $OBSS_PD_{Thr} \leftarrow Beacon_{RSSI} - M$
if $OBSS_PD_{Thr} > OBSS_PD_{ThrMax}$ **then**
 $OBSS_PD_{Thr} \leftarrow OBSS_PD_{ThrMax}$
 $TXPWR \leftarrow TXPWR_{Min}$
else if $OBSS_PD_{Thr} < OBSS_PD_{ThrMin}$ **then**
 $OBSS_PD_{Thr} \leftarrow OBSS_PD_{ThrMin}$
 $TXPWR \leftarrow TXPWR_{Max}$
else
 $TXPWR \leftarrow OBSS_PD_{ThrMin} +$
 $TXPWR_{ref} - OBSS_PD_{Thr}$
end
return $OBSS_PD_{Thr}, TXPWR$

Algorithm 1: RTOT algorithm

the transmission power, assuming that the further away is a STA, the less it should seek for SR improvements. While $Beacon_{RSSI}$ value is related to the distance, it is unlikely to be comprised in the range $[OBSS_PD_{ThrMin}, OBSS_PD_{ThrMax}]$. Thus, a translation from the $Beacon_{RSSI}$ value space to the $OBSS_PD_{Thr}$ one is needed. We introduce M for this purpose.

RTOT proceeds as follow:

- 1) $OBSS_PD_{Thr}$ is computed
- 2) if the computed $OBSS_PD_{Thr}$ is larger than $OBSS_PD_{Max}$, i.e., $Beacon_{RSSI}$ value is large, $OBSS_PD_{Thr}$ is set to $OBSS_PD_{Max}$ and the $TXPWR$ is equal to $TXPWR_{Min}$. The node is configured to seek for maximal SR.
- 3) if the computed $OBSS_PD_{Thr}$ is smaller than $OBSS_PD_{Min}$, i.e., $Beacon_{RSSI}$ value is small, $OBSS_PD_{Thr}$ is equal to $OBSS_PD_{Min}$ value and the $TXPWR$ is set to $TXPWR_{Max}$. The node is not configure to seek for any SR improvement.
- 4) if the computed $OBSS_PD_{Thr} \in (OBSS_PD_{Min}, OBSS_PD_{Max})$, i.e., $Beacon_{RSSI}$ value is moderate, the $TXPWR$ is computed using (2). The node is configured to seek for SR improvement.

It is worth mentioning that the choice to compute $OBSS_PD_{Thr}$ first has been done in order to work in a way similar than DSC solution which is the other SR improvement solution proposed at IEEE. This choice will allow future comparisons between these two solutions. Moreover, using beacon RSSI as a base for RTOT does not impose any hardware or standard modification, and provides a simple method to evaluate $OBSS_PD$ -based SR performance.

V. SIMULATION SETUP

To study RTOT algorithm performance, we use the enterprise scenario described in TGax simulation scenarios document [7]. This scenario is adequate in term of SR study as it represents a high density deployment comprising a big number of STAs (2048) and APs (32) in a small area (40 m * 80 m).

Figure 4 depicts the enterprise scenario. The topology is made of 8 offices separated by walls, each office being made

Table II: Physical and MAC layer parameters

Parameters	Values	Parameters	Values
IEEE standard	802.11ac	$TXPWR_{AP}$	20 dBm
Bandwidth	80 MHz	MCS	5
Traffic Type	Uplink UDP CBR	Propagation Loss	Log-distance 2 exponents
MPDU size	1538 bytes	Wall Loss	7 dB
Aggregation	32 MPDUs	Legacy CST	-76 dBm
STA $TXPWR_{Max}$	15 dBm	M_{min}	8 dBm
STA $TXPWR_{Min}$	3 dBm	M_{max}	33 dBm

of 64 cubicles and containing 4 APs. Each cubicle contains 4 STAs which gives a number of 2048 STAs in the topology. Four non-overlapping 80 MHz channel are affected to the four APs of each office and each AP manages 16 cubicles i.e. 64 STAs are connected to each AP.

Table II summarizes the parameters used for the simulations conducted using ns-3 simulator [21]. Each STA sends UDP CBR traffic to its AP in order to saturate the medium using a MCS of 5 (around 200 Mbps). The APs use a fixed transmission power ($TXPWR_{AP}$) of 20 dBm, while the STAs minimum ($TXPWR_{Min}$) and maximum ($TXPWR_{Max}$) transmission powers are set to 3 dBm and 15 dBm, respectively. RTOT algorithm is bounded by the transmission power, i.e., STA $TXPWR \in [TXPWR_{Min}, TXPWR_{Max}]$. Thus, we vary the M margin value in the range $[M_{min}, M_{max}]$ where:

- M_{min} is the margin value that leads all STAs in the topology to use $OBSS_PD_{ThrMax}$ and to transmit with a power of $TXPWR_{Min}$. Therefore, even STAs the furthest away from their AP transmit with a small power. This margin value could allow the maximum SR improvement but tends to be risky.
- M_{max} is the margin value that leads all STAs in the topology to transmit with their $TXPWR_{Max}$. It results in closest nodes from the AP to transmit with their maxi-

imum transmission power. $OBSS_PD_{Thr}$ that produces a transmission power of 15 dBm is -68 dBm.

M_{min} and M_{max} are computed by using the propagation loss model, and have respectively a value of 8 dBm and 33 dBm.

The metrics used for RTOT evaluation are the following: the aggregate throughput of all BSSs (total number of bytes received successfully by APs per second), the average throughput per-STA (average number of bytes successfully sent to AP per STAs per second) and 5th percentile throughput per-STA (average throughput per-STA for the 5 % STAs exhibiting the lowest throughput), and the fairness computed thanks to the the goodput ratio. Goodput ratio for a station i is given by (3).

$$GR_i = \frac{R_i}{T_i} \quad (3)$$

where R_i is the number of UDP packets correctly received by the AP on which the STA i is associated and T_i is the number of UDP packets generated by the station i . The following results correspond to 50 independent simulations for each M value.

VI. SIMULATION RESULTS AND DISCUSSION

In this section, we compare the enterprise scenario performance for devices using OBSS_PD-based SR with RTOT algorithm and legacy devices. Based on the results obtained for RTOT, we also provide recommendations for designing new algorithms for OBSS_PD-based SR and study their efficiency.

Figure 5 shows the overall results for the metric defined in Section V. We can observe that the margin value highly influences the results and that three different zones can be clearly identified, Zone 1 (smallest margin between 8 dBm and 15 dBm), Zone 2 (margin between 16 dBm and 20dBm) and Zone 3 (margin between 21 dBm and 33 dBm).

For Zone 1, we observe the worst performances of RTOT algorithm. The aggregate throughput is 30 % lower than legacy's one (Figure 5a); there is around 80 % of STAs unable to successfully send a single packet (Figure 5b), which obviously translate to low average per-STA throughput (Figure 5c). Our analysis shows that Zone 1 margin values result in RTOT to be too aggressive. Indeed, the transmission power computed by RTOT (3 dBm) is too weak to allow the furthest away STAs transmission to be decoded by their respective APs. These results show that OBSS_PD-based SR parametrization is of crucial importance as wrong parameters could result in some STA being unable to communicate. Thus, we recommend algorithms implementing OBSS_PD-based SR to be adaptive in order to be able to react dynamically to incorrect OBSS_PD-based SR parametrization.

Zone 2 (margin between 16 dBm and 20 dBm) features an increase of the aggregate throughput around 55 % compared to the legacy one as shown on Figure 5a. Moreover, we can see on Figure 5b that the system's fairness is significantly improved with around 90 % of STAs sharing a goodput ratio between 0.3 and 0.5 while for legacy's case, around 70 % of STAs has a goodput ratio smaller than 0.3. Finally, we can observe first on Figure 5c that every margin value of Zone 2 increases both the

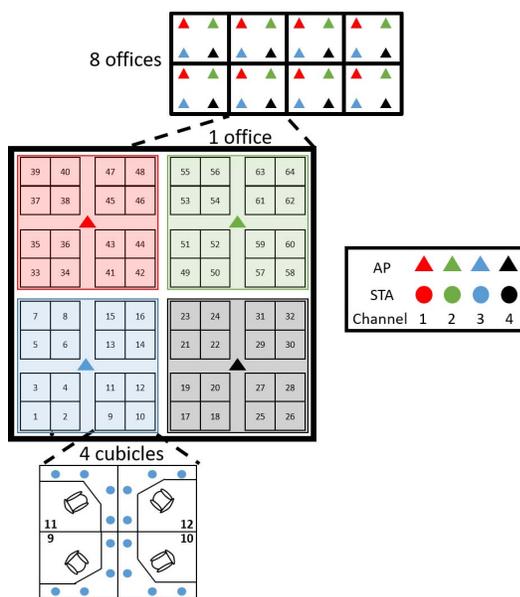
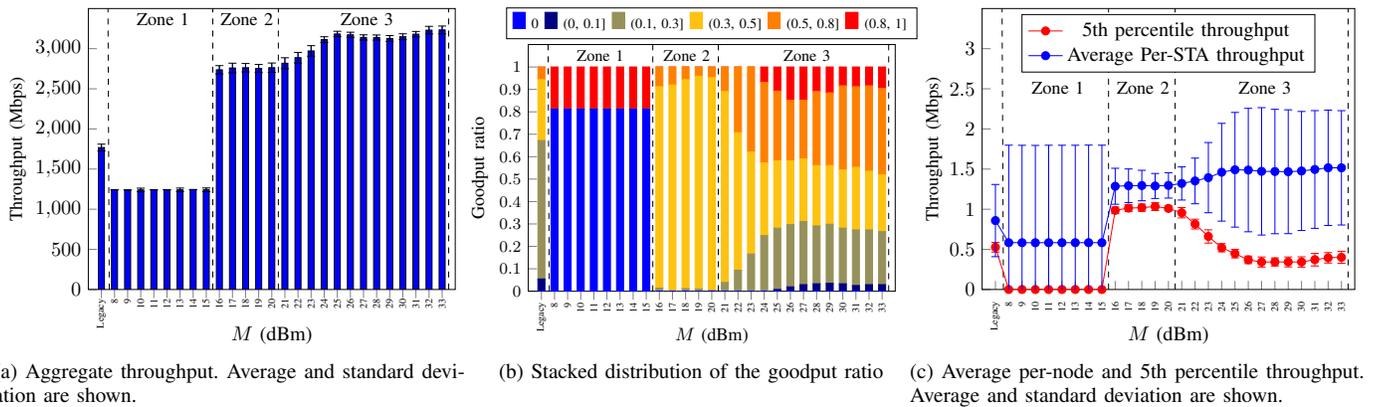


Figure 4: Enterprise scenario topology

Figure 5: Overall results for every M value (50 runs per M value)

average per-node and 5th percentile throughput compared to the legacy's case. Then, the 5th percentile average throughput is close to the average throughput per-STA (20 % of difference). It indicates that RTOT algorithm is able to improve both system overall throughput and fairness among STAs compared to legacy case.

Zone 3 exhibits the maximum increase regarding the aggregate throughput with an improvement up to 80 % as represented on Figure 5a. However, as shown on Figure 5b, the system fairness decreases as the margin increases. The larger is the margin, the larger is the percentage of STAs experiencing a goodput ratio smaller than 0.1, while the larger the percentage of STAs experiencing a goodput ratio higher than 0.5. The increase in aggregate throughput comes at the price of unfairness with some STAs experiencing a large throughput while some others being barely able to transmit. Finally, on Figure 5c, we can see first that while the average per-node throughput is larger than the legacy's one for every margin value, the average 5th percentile throughput becomes smaller than the legacy's one when the margin is larger than 25 dBm. Then, we can observe that the larger the margin is, the larger is the difference between average throughput and 5th percentile throughput (up to 74 % difference). These results show first that there is a trade-off between the reachable gain for overall throughput and the fairness. Then, it reveals that the aggregate throughput metric should not be the only metric to study SR techniques performance and that the fairness should be considered.

Figure 6 shows the goodput ratio observed for a margin value of 16, 22 and 33 dBm in the 2D plane. For the clarity of the presentation, only one 80 MHz channel (channel 1 on Figure 4) is displayed but it is worth mentioning that each channel exhibits the same behavior. Comparing these three Figures allows us to evaluate the evolution of fairness.

For a margin value of 16 dBm, almost every STAs exhibits the same goodput ratio (around 0.3) with the exception of STAs close to their AP (around 0.5). The 16 dBm margin case results in the $OBSS_PD_{Thr}$ and $TXPWR$ used per-STA to be highly distributed among STAs. STAs close to the AP experience a higher goodput ratio due to the fact that they

are still using $OBSS_PD_{ThrMax}$, which provides for a higher transmission opportunity. Increasing the margin to 22 dBm leads to two improvements for the STAs close to their AP: the goodput ratio goes from 0.5 to 0.8 and the zone experiencing this goodput ratio has been extended compared to the 16 dBm case. On the other hand, we notice that edge STAs belonging to different APs, see their goodput ratio decrease dramatically (e.g. upper edge STAs for AP2 and AP3 and bottom STAs for AP 6 and 7). Finally, edge STAs associated to the edge APs (AP 1, 4, 5 and 8) and located on the opposite of another AP (bottom left STAs of AP1 for example) see their goodput ratio increase close to 0.5. The margin value of 22 dBm corresponds to the first furthest away STAs from their AP to use $OBSS_PD_{ThrMin}$. It starts to be problematic for edge STAs associated with the AP located in the middle of the topology as they assert the channel to be busy too often and become starved, leading to unfairness. Edge STAs associated with APs located on the edge does not suffer from this problem as there are less concurrent OBSS transmissions. Finally, the STAs close to the AP see their goodput ratio increase as their transmission chances increase since they are using a larger $OBSS_PD_{Thr}$ compared to the furthest away STAs. Increasing the margin strengthen this tendency and thus the unfairness as shown on Figure 6c for a margin of 33 dBm. These results show the complexity of the SR improvement problem. SR impacts drastically the overall performances of the system and could clearly leads to unfairness if not used wisely.

Recommending an optimal margin value for RTOT algorithm in the enterprise scenario highly depends on the desired objectives. If the ultimate goal is to reach the maximum aggregate throughput, then a margin value of 33 dBm is recommended for the enterprise scenario with a throughput increase by a factor of 1.8 compared to a legacy network. However, the fairness is not guaranteed for some STAs and we observe a decrease of the 5th percentile throughput per-STA by a factor of 1.3 while the IEEE 802.11ax aims to increase the throughput per-node by a factor of 4. A margin value of 19 dBm seems optimal for the enterprise scenario with an increase of the aggregate throughput by a factor of 1.55 and

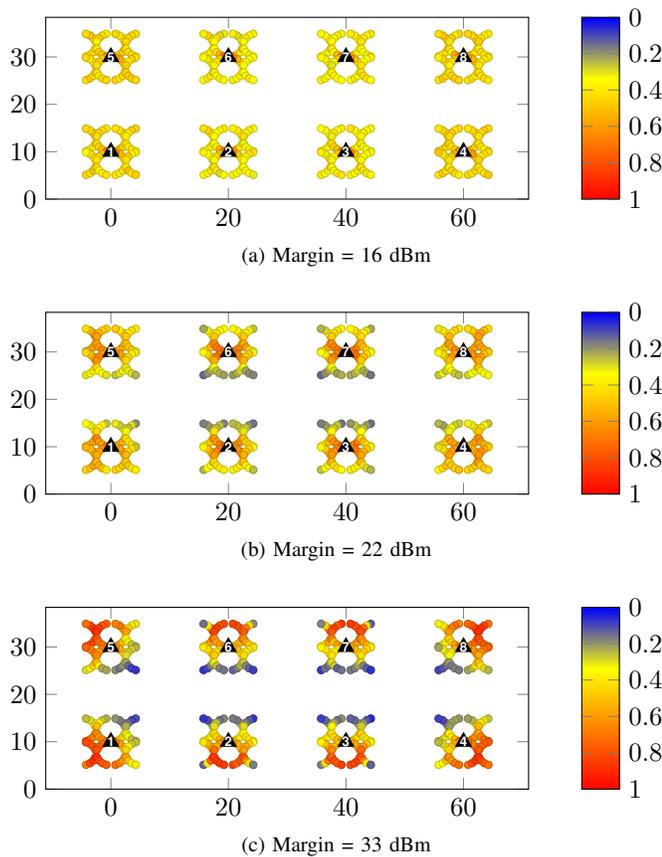


Figure 6: Goodput ratio in the 2D plane. The triangles represents the APs while the circles represents the STAs. STA color indicates its goodput ratio.

an increase of the 5th percentile per-STA throughput of 1.98.

VII. CONCLUSION

In this paper, we evaluated the RTOT algorithm for OBSS_PD-based SR solution proposed at IEEE 802.11ax to improve SR in dense environments. The TGax group objective is to improve the average throughput per-STA by a factor of four. We have seen in this paper that RTOT allows to improve the throughput by a factor close to two in the enterprise scenario. However, for a maximum throughput increase, the fairness is not always guaranteed. This shows the trade-off between maximum reachable throughput and fairness. Combining OBSS_PD-based SR with other techniques such as Multi-User MIMO, MPDU-aggregation, or channel bonding should allow to reach the targeted four factor.

RTOT is to the best of our knowledge the first algorithm implementing OBSS_PD-based SR. This method dynamic could be improved by taking into account for example the number of beacon missed in order to react and adapt faster OBSS_PD-based SR and transmission power. An other interesting approach could be also to use cross-layer information such as number of retransmissions in order to dynamically compute the $OBSS_PD_{Thr}$ based on the link quality.

Finally, SR improvements techniques highly depends on the tested topology (AP and STA density, mobility) and we plan to investigate RTOT performances in other relevant scenarios (residential apartment, stadium) in order to provide further recommendations.

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