On the Performance of the Spatial Reuse Operation in IEEE 802.11ax WLANs

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Abstract—The Spatial Reuse (SR) operation included in the IEEE 802.11ax-2020 (11ax) amendment aims at increasing the number of parallel transmissions in an Overlapping Basic Service Set (OBSS). However, many unknowns exist about the performance gains that can be achieved through SR. In this paper, we provide a brief introduction to the SR operation described in the IEEE 802.11ax (draft D4.0). Then, a simulation-based implementation is provided in order to explore the performance gains of the SR operation. Our results show the potential of using SR in different scenarios covering multiple network densities and traffic loads. In particular, we observe significant performance gains when a WLAN applies SR with respect to the default configuration. Interestingly, the highest improvements are observed in the most pessimistic situations in terms of network density and traffic load.

Index Terms—spatial reuse, IEEE 802.11ax, performance, simulation

I. INTRODUCTION

The IEEE 802.11ax (11ax) amendment, which official publication is due to be released in June 2020, is expected to lay the groundwork of next-generation (NG) Wireless Local Area Networks (WLANs). One of the main goals of this amendment is to improve network efficiency by increasing the number of parallel transmissions in an Overlapping Basic Service Set (OBSS). To that purpose, the Spatial Reuse (SR) operation is introduced along with other techniques to boost the performance of NG WLANs, from which we highlight Orthogonal Frequency-Division Multiple Access (OFDMA) or Downlink/Uplink Multi-User Multiple-Input-Multiple-Output (DL/UL MU-MIMO) [1].

The SR operation is based on sensitivity adjustment together with Transmission Power Control (TPC). In particular, a specific OBSS Packet Detect (OBSS/PD) threshold is employed for the detected OBSS transmissions (also referred to as inter-BSS transmissions), so that channel utilization can be enhanced. Moreover, in order not to affect any ongoing

transmission, a node applying SR must limit its transmit power as a function of the OBSS/PD.

Fig. 1 depicts a use case where the SR operation could potentially improve the network efficiency of an OBSS. Notice that the dashed lines in the figure indicate the carrier sense area of each device, provided that the transmit power of the others is fixed and that the same channel is used. As illustrated, the default Clear Channel Assessment Carrier Sense (CCA/CS) threshold would not allow simultaneous transmissions to be held between Access Points A and B (AP_A and AP_B). In that case, each WLAN should defer its transmission when the other occupies the channel, due to the application of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Nevertheless, by properly increasing the OBSS/PD threshold of AP_A, both devices would be able to transmit at the same time, thus improving the utilization of the channel.
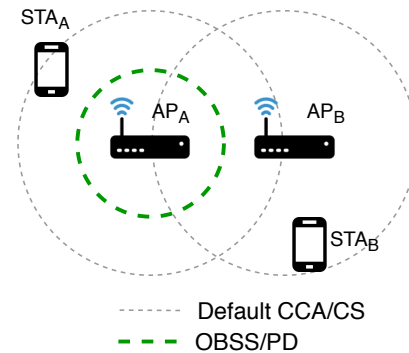

Fig. 1. Example of the potential of the 11ax SR operation.

Despite SR is expected to bring significant performance gains to WLANs, its actual benefit is still unknown. First, the new kind of inter-WLAN interactions that the operation generates is unexplored, as well as their impact on the network. Moreover, the gain achieved by applying SR is hindered by the trade-off between the number of parallel transmissions and their duration. Note that increasing the OBSS/PD (i.e., using a more aggressive threshold) entails decreasing the transmission power, which may result in using a lower Modulation and Coding Scheme (MCS), or even experiencing an increased packet error rate. The effects of increasing the OBSS/PD,

	Data rate	Channel access probability	Hidden-node probability	Exposed-node probability
OBSS/PD ↑ (Tx Power ↓)	↓	↑	↑	↓

and hence decreasing the transmission power, are illustrated in Table I. As shown, an increase in the OBSS/PD threshold entails a higher probability for accessing to the channel, since the number of sensed inter-BSS transmissions can be potentially reduced (this is equivalent to reducing the exposed-node probability). In contrast, the number of hidden nodes can potentially increase as the listening area is being reduced.

In this work, we shed light on the performance of the 11ax SR operation and highlight the situations in which it is worth using it. The main contributions of this paper are as follows:

- We provide a summary of the OBSS PD-based SR operation included in draft version D4.0 of the IEEE 802.11ax amendment, which is, to the date of publishing this article, under the initial sponsor ballot phase.
- We present an implementation of the aforementioned operation in the 11ax-based Komondor simulator [2].[1]
- We evaluate the performance of the SR operation through simulations, thus assessing its potential for next-generation wireless networks. Different network densities and traffic loads are considered for covering the analysis of multiple use cases.

II. RELATED WORK

The 11ax SR operation included has been previously surveyed and evaluated in [1], [3]–[5]. However, these works refer to previous draft versions of the amendment (D1.0 and D2.0), which has undergone significant modifications in its current version D4.0.

First, the Task Group ax (TGax) presented some preliminary results for cellular-type scenarios in [4]. In particular, significant gains were shown when combining BSS Coloring and Dynamic Sensitivity Control (DSC) [6]. A further analysis was then provided in [5] for office scenarios, which also showed that gains were only achieved in dense deployments. Nonetheless, the simulations conducted in that work were obtained from a system and link level integrated simulation platform based on ns-2, from which no validation was provided.

The authors in [7] provided a thorough performance evaluation of the SR operation, in addition to several other features included in the 11ax amendment. To that purpose, they proposed their own simulation platform for IEEE 802.11ax (SLISP), which mostly focuses on the MAC of the 11ax. Based on that, the SR operation was evaluated in indoor and outdoor scenarios containing multiple BSS. Significant gains were

shown in indoor deployments (especially for downlink traffic), while a moderate gain was noticed in outdoor situations.

As shown, few works attempt to provide a performance evaluation of the SR operation through simulations. The main cause lies in the novelty of the mechanism, which entails a lack of reliable simulation platforms that include 11ax features. To the date of publishing this article, SR is still under development for ns-3.[2] In order to address such a lack of reliable tools, in this work we provide an implementation of the SR operation in the Komondor simulator.[3] Moreover, our results are gathered based on the newest draft version (D4.0).

III. SPATIAL REUSE OPERATION

The 11ax SR operation is divided into two different mechanisms, which are independent. On the one hand, we find the OBSS PD-based SR operation, whereby 11ax nodes can detect SR opportunities from inter-BSS transmissions by using a more aggressive CCA policy. On the other hand, the Spatial Reuse Parameter (SRP)-based SR operation is provided, which performs similarly but only taking advantage of trigger-based communications [8]. Throughout this document, we will exclusively refer to the first mechanism (i.e., OBSS PD-based SR) because of the development cost of building trigger-based transmissions required for the SRP-based SR operation. In addition, the slow adoption of 11ax in WLANs would prevent using full scheduling transmissions schemes, in favor of CSMA/CA ones. Notwithstanding, both mechanisms are expected to lead to similar results since the procedure of adjusting the OBSS/PD is similar.

A. BSS Coloring and Spatial Reuse Groups

The whole SR operation is based on identifying the source of a given transmission, i.e., inter-BSS frame detection. The idea is that High Efficiency (HE) nodes - a.k.a 11ax nodes - can rapidly decode the MAC headers of a certain transmission, and determine its origin. Then, a more aggressive OBSS/PD threshold can be employed to increase the probability of accessing to the channel.

For the fast packet source identification, two concepts are introduced, which stand for BSS Coloring and Spatial Reuse Groups (SRG). On the one hand, the BSS Color field is included in the PHY headers[4] to uniquely identify different WLANs belonging to an OBSS. In case of detecting a color collision, the affected WLANs would require to change their BSS Color. On the other hand, SRGs can be formed by a set of overlapping WLANs. The SRG field is present in control frames such as Beacons, Probe responses, or (Re)Association responses.[5] In this case, a specific OBSS/PD threshold can be used for transmissions within the same SRG.

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[2]All the new developments in ns-3 are published in the following repository: https://gitlab.com/nsnam/ns-3-dev

[3]The validation of the Komondor simulator can be found in [2].

[4]The BSS Color is carried in the HE-SIG-A field, which is present in every Physical Layer Convergence Procedure (PLCP) Protocol Data Unit (PPDU).

[5]Unlike the BSS Color, the SRG is included in the Spatial Reuse Parameter Set (SRPS) element. A bitmap is stored by each 11ax node applying SR, which maps the set of BSS Colors that belong to a certain SRG.
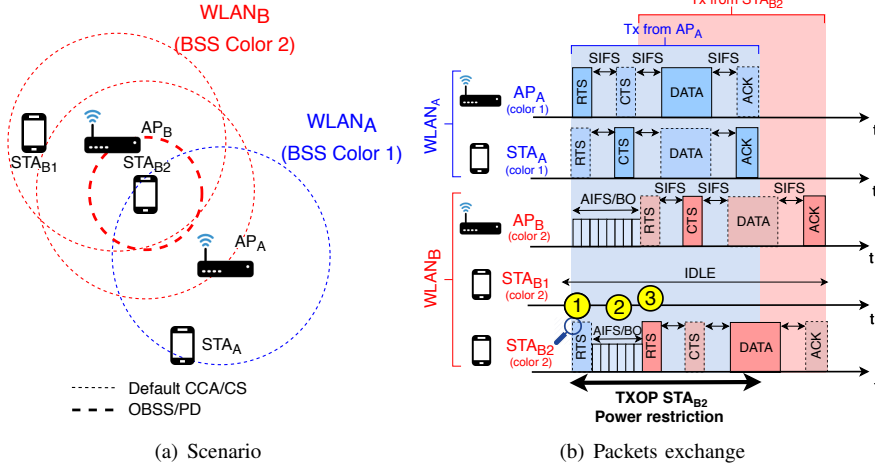
Fig. 2. Example of applying the OBSS PD-based SR operation.

B. General Constraints

The 11ax amendment includes a set of constraints on defining the OBSS/PD to be used for detecting SR opportunities. In particular, the OBSS/PD cannot exceed the following upper bound:

$$
\text{OBSS/PD} \leq \max \Big(\text{OBSS/PD}_{\min}, \min \big(\text{OBSS/PD}_{\max}, \\
\text{OBSS/PD}_{\min} + (\text{TX\_PWR}_{\text{ref}} - \text{TX\_PWR}) \big) \Big),
$$

where $\text{OBSS/PD}_{\min}$ and $\text{OBSS/PD}_{\max}$ are set to -82 dBm and -62 dBm, respectively, the reference power $\text{TX\_PWR}_{\text{ref}}$ is set to 21 or 25 dBm, according to the capabilities of the device,[6] and TX_PWR is the transmission power in dBm.

In order to regulate the transmissions held during SR-based opportunities, the transmission power is limited according to the OBSS/PD threshold used for detecting those opportunities. In case that $\text{OBSS/PD} \leq \text{OBSS/PD}_{\min}$, the transmission power is unconstrained. Otherwise, the maximum allowed transmission power $\text{TX\_PWR}_{\max}$ is given by:

$$
\text{TX\_PWR}_{\max} = \text{TX\_PWR}_{\text{ref}} - (\text{OBSS/PD} - \text{OBSS/PD}_{\min}) \quad (1)
$$

C. Example of the OBSS PD-based Spatial Reuse Operation

In order to illustrate the concepts described above, let us consider the scenario depicted in Fig. 2(a). As shown, there is a station (STA), namely STA_{B2}, which, by using the default configuration, is prone to suffer from flow starvation, as a result of the OBSS interference. Nevertheless, the OBSS PD-based SR operation allows that STA to overcome the aforementioned interference, thus gaining access to the channel. This is illustrated in Fig. 2(b), where inter-BSS transmissions are ignored by STA_{B2} when using the SR operation. In marker 1 (shown in yellow), STA_{B2} inspects the Request to Send (RTS) frame sent by AP_A, which is identified as an inter-BSS transmission. Accordingly, STA_{B2} uses a more aggressive

OBSS/PD threshold, which allows the backoff procedure to be resumed (marker 2). Finally, STA_{B2} starts its own transmission by taking advantage of the detected SR-based opportunity (marker 3). However, a power restriction is applied, thus decreasing the MCS and increasing the data transmission time, as a consequence.

IV. IMPLEMENTATION OF OBSS PD-BASED SR IN KOMONDOR

The Komondor simulator was conceived, among other purposes, to allow the low-complexity integration of novel mechanisms included in new IEEE 802.11 standards. In this Section, we briefly introduce the implementation conceived for the SR operation.[7]

Fig. 3 shows a flowchart that summarizes the SR implementation for a given HE node in case of detecting a single inter-BSS transmission. The most important groups of functionalities (highlighted with numbers in the figure) are described in detail in the following subsections.
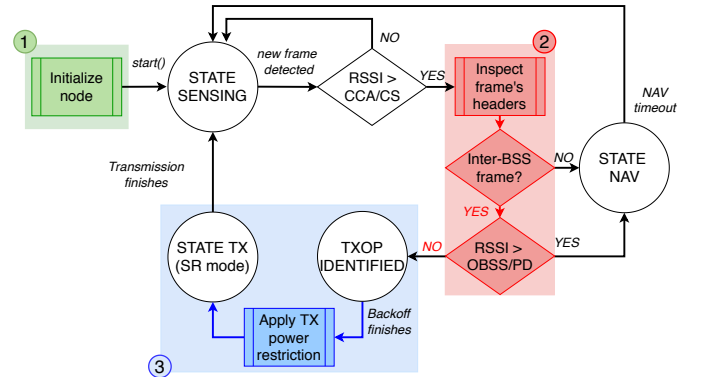
Fig. 3. Flowchart of the SR implementation for a given HE node when detecting a single inter-BSS transmission.

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[6]The $\text{TX\_PWR}_{\text{ref}}$ can be set to either 21 or 25 dBm, depending on the transmission capabilities of the HE node with regards to the highest supported number of spatial streams (NSS).

[7]The code used for the simulations of this paper can be found in pre-release v3.0 (https://github.com/wn-upf/Komondor/releases/tag/3.0).

A. Initialization

First of all, any node that applies SR must indicate support for it. In addition, the parameters related to the SR operation should be introduced, which are as follows:

- **BSS Color**: identifier of the BSS to which the node belongs to. The BSS Color identifies WLANs uniquely.
- **Spatial Reuse Group (SRG)**: identifier of the group to which the node belongs.
- **Non-SRG OBSS/PD**: the sensitivity threshold to be used for generic inter-BSS transmissions.
- **SRG OBSS/PD threshold**: the sensitivity threshold to be used for inter-BSS transmissions that are originated by nodes belonging to the same SRG.

For the sake of efficiency, the PHY is simplified in the Komondor simulator, so that particular focus is put on the MAC layer. Moreover, operations related to management and control are simplified too. According to that, the initialization of nodes is logically performed at the beginning of the simulation, instead of simulating the exact exchange of control frames between nodes. In particular, the AP of a given WLAN is meant to notify to its associated STAs the initial SR configuration, as well as any potential change, which in Komondor is done virtually (i.e., without the actual packet exchanges).

B. Detection of SR-based Opportunities

Once the simulation starts and nodes begin to exchange packets, it is possible to detect SR-based opportunities from inter-BSS frames. For that, a certain node must first analyze the headers of any detected frame and rapidly identify its source. During this stage, the node will assess whether the transmitter belongs to the same WLAN (intra-BSS) or not (inter-BSS). Moreover, in case of being of kind inter-BSS, the frame is sub-categorized into SRG or non-SRG, according to the groups established during initialization.

In case of detecting an intra-BSS transmission, the default CCA/CS threshold is used. Otherwise, the corresponding OBSS/PD threshold (non-SRG or SRG) is applied. In accordance with that, the power received P_{rx} from the incoming transmission is used to identify potential SR-based opportunities. In particular, the following two conditions must hold: 1) $P_{rx} \geq$ CCA/CS, and 2) $P_{rx} <$ OBSS/PD.

C. Transmit under the SR mode

In case of having detected an SR-based opportunity, an HE node will continue decreasing its backoff, provided that the channel status allows to do so. Once the backoff counter is over and the node is about to transmit, a transmit power limitation is applied. In particular, the transmit power is adjusted according to (1). Finally, once the HE node finishes its SR-based transmission, it returns to the default sensing state, where channel access is scheduled according to the legacy CCA/CS threshold (given that more packets are waiting for transmission in the buffer).

It is important to notice that several SR-based opportunities can be detected before transmitting, due to the multiple reception of different inter-BSS frames. In that case, the most restrictive power limitation must be applied.

V. SIMULATION SETUP

In this Section, we depict the simulation environment that has been considered for evaluating the performance of the SR operation.

A. Channel Model

Path-loss effects are characterized according to the TMB 5GHz indoor model for IEEE 802.11ac/11ax WLANs [9]. In particular, the path-loss PL_{TMB} between a transmitter i and a receiver j that are separated by $d_{i,j}$ meters is given by (2):

$$PL_{TMB}(d_{i,j}) = L_0 + 10 \cdot \gamma \cdot \log_{10}(d_{i,j}) + k \cdot \overline{W} \cdot d_{i,j}, \quad (2)$$

where L_0 is the path-loss intercept, γ is the path-loss exponent, k is the attenuation factor that characterizes obstacles, and $\overline{W}$ is the average number of wall obstacles per meter.

B. Traffic Generation and Data Rate

Only downlink transmissions are considered for the sake of capturing inter-AP interactions. Hence, a traffic generator is attached to every AP. All traffic generators produce data packets at the same traffic load ℓ, which varies depending on the scenario. The packets arrival process is modeled through a Poisson distribution.

The rate at which data is transmitted is based on the MCS modes defined in the 11ax amendment, which are virtually selected according to the Signal-to-interference-plus-noise ratio (SINR) perceived at the receiver (the STA) from its transmitter (the AP). The highest achievable data rate is achieved when using modulation 1024-QAM at a coding rate of 5/6.

C. Throughput Calculation and Reception Model

Nodes operate under the CSMA/CA protocol, and use the SR operation on top of that. Since Komondor simulates the actual exchange of packets between nodes in a WLAN, the throughput S experienced by it is directly obtained from:

$$S = \frac{[\text{Data bits transmitted successfully}]}{[\text{Total simulation time}]}$$

The number of data bits (or data packets) transmitted successfully depends on the channel conditions and the sensed interference. In particular, a given transmission is considered to be successful only if the following conditions hold at the receiver:

1) The power of interest sensed at the receiver remains above the CCA/CS.
2) The SINR stays above the capture effect (CE) threshold, set to 10 dB.

D. Scenarios for Evaluation

The 11ax SR operation is evaluated in random scenarios as the one depicted in Fig. 4. Notice that, for the sake of illustrating the potential of SR, only the WLAN in the middle (namely, WLAN$_A$) applies the SR operation, while the others remain using the default CCA/CS. WLAN$_A$ is placed at the center of the scenario, so that it is exposed to a higher level of interference than the others. We consider that all the WLANs are operating in the same channel, as otherwise, they would not interact.
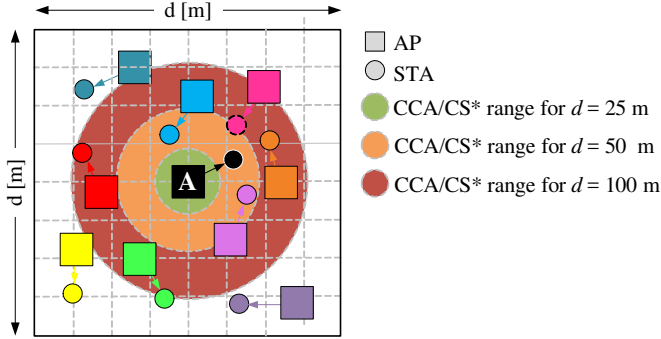

Fig. 4. Random deployment with WLAN$_A$ placed in the center. Note that we include the CCA/CS* range of WLAN$_A$ in the map – corresponding to maximum transmission power (20 dBm) and minimum CCA (-82 dBm) – for the sake of representing the three considered map densities.

Different network densities are considered, which is useful to evaluate the gains achieved by the 11ax SR operation in different use cases. In particular, we consider low-density (LD), medium-density (MD), and high-density (HD) scenarios. In summary, we simulate multiple scenarios accounting for $N_m = 3$ maps of sizes 25×25, 50×50, and 100×100 m², $N_d = 50$ different random deployments (i.e., nodes allocation), $N_{cca} = 21$ OBSS/PD values ranging from -62 to -82 dBm, and $N_\ell = 16$ traffic loads ranging from $\ell = 1$ to 100 Mbps. In total, $N_s = N_m \times N_d \times N_{cca} \times N_\ell = 50,400$ scenarios (or Komondor inputs) are simulated. The observation time for each simulation is $T = 10$ seconds.

E. Simulation Parameters

The 11ax PHY and MAC parameters used in the simulations are listed in Table II.

VI. PERFORMANCE EVALUATION

Based on the simulation setup described in Section V, we evaluate the potential of the 11ax SR operation in various situations. In particular, for each network density and traffic load, we measure the maximum performance gain that can be achieved by WLAN$_A$ when applying SR. This upper bound is provided by the OBSS/PD value that maximizes the average throughput over 50 different random deployments. We also assess the impact that such an optimal SR configuration (from WLAN$_A$'s perspective) produces on the environment (i.e., the other WLANs). Specifically, we compare the throughput, channel occupancy and delay obtained by all the other WLANs

TABLE II
SIMULATION PARAMETERS.

|	Parameter	Value
PHY	Central frequency f_c	5 GHz
	Transmission gain G_{tx}	0 dB
	Reception gain G_{rx}	0 dB
	Capture Effect threshold CE	10 dB
	Path-loss (TMB) PL$_{TMB}(d)$	See (2)
	Path-loss intercept L$_0$	54.120
	Path-loss exponent γ	2.06067
	Attenuation factor k	5.25
	Average num. of walls per meter W	0.1467
	Background noise level N	-95 dBm
	Legacy OFDM symbol duration σ_{leg}	4 µs
	OFDM symbol duration (GI-32) σ_{32}	16 µs
	Number of subcarriers (20 MHz) N_{sc}	234
	Number of spatial streams N_{ss}	1
	Transmit power levels $\mathcal{T}$	1 to 20 dBm (1 dBm steps)
MAC	Empty slot duration T$_e$	9 µs
	SIFS duration T_{SIFS}	16 µs
	DIFS/AIFS duration $T_{DIFS/AIFS}$	34 µs
	PIFS duration T_{PIFS}	25 µs
	Legacy preamble duration $T_{PHY\text{-}leg}$	20 µs
	HE single-user field duration $T_{HE\text{-}SU}$	100 µs
	ACK duration T_{ACK}	28 µs
	Block ACK duration T_{BACK}	32 µs
	Size OFDM symbol (legacy) $L_{s,l}$	24 bits
	Length of data packets L$_d$	12,000 bits
	Max. No. of frames in an A-MPDU N_{agg}	64
	Length of an RTS packet L_{RTS}	160 bits
	Length of a CTS packet L_{CTS}	112 bits
	Length of service field L_{SF}	16 bits
	Length of MAC header L_{MH}	320 bits
	Max. contention window (fixed) CW	15
	Allowed sensitivity levels $\mathcal{S}$	-82 to -62 (1 dBm steps)
Other	Traffic model Λ	Downlink
	Traffic load ℓ	1 to 100 Mbps
	Map area A	25x25, 50x50 and 100x100 m²
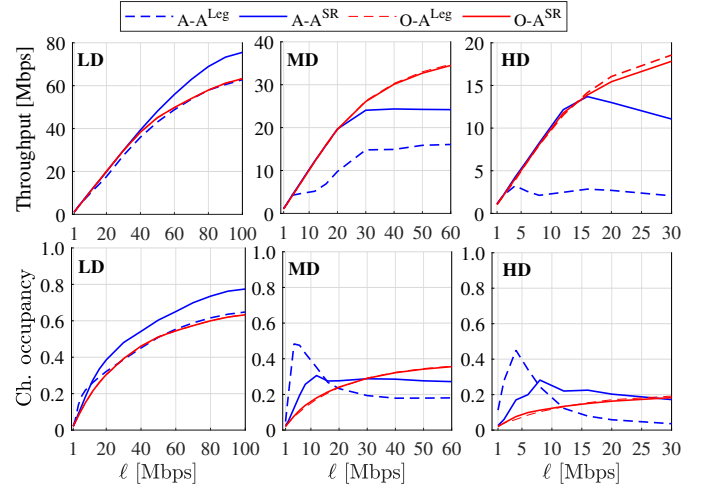
Fig. 5. Throughput and channel occupancy experienced by WLAN$_A$ (A) and the other WLANs (O) in low (LD), medium (MD) and high density (HD) deployments. Each curve is named in the legend in the format X-A^m, where A^m represents whether WLAN$_A$ uses spatial reuse (SR) or not (Leg).

in two situations: *i)* the legacy CCA/CS is used by the entire network (including WLAN$_A$), and *ii)* Only WLAN$_A$ applies the SR using the optimal OBSS/PD for its own interests.

Fig. 5 shows the highest gains that can be achieved both in throughput and channel occupancy when WLAN$_A$ implements the SR operation. As shown in the first row, significant improvements are achieved on WLAN$_A$'s individual throughput, especially for the highest network density. Moreover,
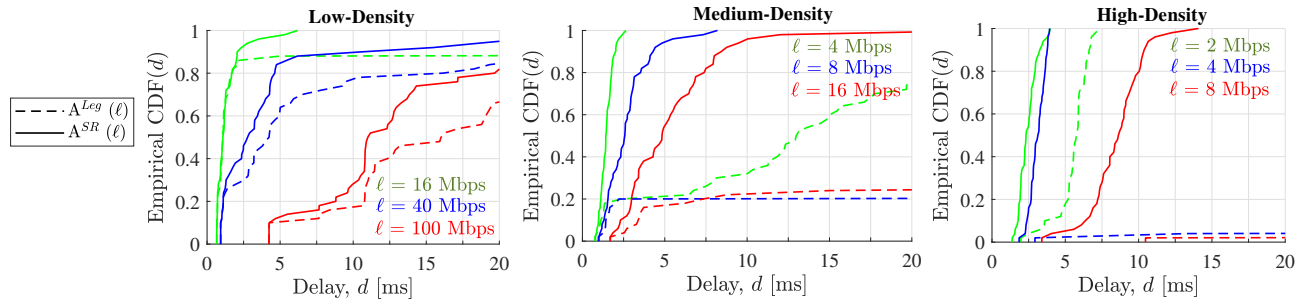
Fig. 6. Empirical cumulative distribution function of the average packet delay experienced by WLAN$_A$. Different network densities and traffic loads are considered. Solid and dashed lines indicate whether WLAN$_A$ uses spatial reuse (SR) or not (Leg), respectively.

importantly, the average throughput achieved by the rest of WLANs is barely affected by the SR operation applied by WLAN$_A$.

Regarding channel occupancy (second row), improvements are also noticed as traffic load increases, for every network density. Essentially, more transmission opportunities are achieved due to the lower OBSS/PD used by WLAN$_A$. Nonetheless, an interesting phenomenon occurs for the MD and HD scenarios at low-moderate traffic loads. In these cases, the legacy approach leads to a clear increase on channel occupancy. This increase is caused by the elevate number of re-transmissions performed, which are propitiated by the higher collision probability between overlapping WLANs. We conclude that SR allows using channel resources more efficiently by reducing the contention among neighboring WLANs, and thus boosting parallel transmissions.

Finally, Fig. 6 illustrates the potential reduction on the delay experienced by WLAN$_A$ when implementing SR. In particular, we select the empirical cumulative distribution function (CDF) to highlight the probability of experiencing small and high delays resulting from all the simulated scenarios. Similarly than before, for each scenario, we pick the average delay obtained by the best possible OBSS/PD threshold used by WLAN$_A$ (in terms of throughput) and compare it with the legacy situation. Three representative traffic load values are included for each network density. As illustrated, the probability of experiencing a high delay rapidly increases with network density and traffic load when legacy operation is considered. Nevertheless, SR substantially improves delay performance by keeping it at moderate values in most of the studied scenarios.

VII. CONCLUSIONS

In this paper, we introduced the 11ax SR operation and evaluated its potential in a variety of scenarios covering different node densities and traffic loads. To that purpose, we provided an implementation of the SR operation in the 11ax-oriented Komondor simulator. Our results showed that significant gains can be achieved by using the SR operation, especially in high interference situations where both network density and traffic load are high. Therefore, there is a huge potential on SR when it comes to maximize channel utilization.

As a future work, the potential of SR will be studied, especially regarding the interactions that occur when more than one WLAN applies the operation. Moreover, the problem of finding the best OBSS/PD will be studied. In this regard, online learning stands as a powerful and suitable solution, due to the complex inter-WLAN interactions that can be generated by using SR. Promising results have been already shown by applying Machine Learning (ML) to address the SR problem [10], [11]. Finally, the interaction of SR with other techniques included in the 11ax (e.g., directional transmissions, target wake time, OFDMA, etc.) is worth to be studied.

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