Preserving Fairness in Super Dense WLANs

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Abstract—**In this paper, after discussing the challenges raised by the increasing density of IEEE 802.11 WLANs, we investigate a new combination of transmit power control and physical carrier sensing adaptation to leverage the spatial reuse in high density deployments. While each of these techniques when applied separately is efficient in enhancing the performance of such dense scenarios, they suffer from serious fairness issues. After highlighting these issues in a dense simulation scenario, a new joint solution is proposed to elevate the unfairness problem especially in the presence of legacy nodes in the network. Extensive simulations show that the proposed technique is able to ameliorate the fairness in different situations, while improving the average throughput by 4 times compared to the standard performance.**

Keywords—Dense Wireless Networks, WLAN, Wi-Fi, IEEE 802.11, 3GPP, Licensed Assisted Access (LAA), MAC protocols, Physical Carrier Sensing (PCS), Clear Channel Assessment (CCA), Transmit Power Control (TPC)

I. INTRODUCTION

Since its first appearance, the IEEE 802.11 Wireless Local Area Networks (WLAN) known as Wi-Fi, gained a very important place between the different wireless communication technologies. This is a result of the inexpensive, easy to use and deploy, and decent performance service offered by this technology. At its first stage, Wi-Fi was meant to replace the Ethernet connections to assure a broadband access to the Internet for end users. Sparse residential deployments were typical for this kind of Wi-Fi usage.

After almost two decades of its introduction, Wi-Fi is witnessing a major change in its usage requirements and deployment scenarios. The rapid proliferation of smartphones and connected objects is drastically multiplying the number of Wi-Fi equipped devices. To assure an ubiquitous coverage for these devices, more and more Access Points (APs) are being deployed. In a typical city, almost in every apartment, a Wi-Fi AP is installed to provide the access to the world wide web. According to [1], in April 2013, 73% of Android smartphones wireless traffic is routed via Wi-Fi. The contribution of Wi-Fi to the total wireless traffic is increased by almost 1% every month.

To relieve the congestion of their cellular networks, mobile operators have identified the importance of mobile data offloading. As a result, the share of offloaded mobile data traffic is expected to increase from 33% in 2012 to 47% in 2017 (see [2]). Authors in [3] conclude that Wi-Fi is the best indoor wireless solution to offload mobile data traffic from cellular networks. Thus, the adoption of Wi-Fi by operators for cellular offloading will continue evolving to keep pace with the exploding increase in mobile traffic.

All the aforementioned facts mean that we are entering the era of super dense Wi-Fi environments. To handle the boom in the demand for wireless communications, densifying is the most sustainable solution as it enhance the spectral efficiency. The sad part is that the original form of Wi-Fi is not made for such a high density deployment. The default contention-based multiple access protocol defined in the IEEE 802.11 standard [4] suffers from serious performance degradation in dense environments.

In order to meet this new reality, the IEEE 802.11ax task group [5] is created to enhance the performance of Wi-Fi in high density scenarios. This group is looking forward for a carrier grade Wi-Fi suitable for mass deployment. Among the discussed solutions to improve the spectral reuse are the control of the transmission power and the adaptation of the carrier sensing mechanism. While these technical solutions have been a subject of many research efforts and standardization contributions, they suffer from fairness issues that prevented their adoption.

This work proposes a new mechanism to jointly adapt the transmission power and the carrier sensing process in order to mitigate the unfairness between the different Wi-Fi nodes. This proposal is meant to be simple yet efficient without introducing serious modification to the current standard. 3GPP is currently specifying LTE operation in the unlicensed band, under the name of Licensed-Assisted Access (LAA). This work is also fully relevant for the design of LAA channel access mechanism, in order to ensure a fair coexistence between different technologies and efficient operation in dense environments.

The rest of the paper is organized as follows. The next paragraph introduces the addressed problem with the related background. Section III discusses the implication of the Signal to Noise Ratio (SINR) and highlights its relation with the adaptation protocols subject of this work. The solution proposed by this paper is presented in Section IV. This proposal is evaluated via extensive simulations in Section V before concluding the work in Section VI.

II. BACKGROUND

The Distributed Coordination Function (DCF) is defined in the standard [4] as the spine of the Media Access Control (MAC) functionality. The operation of DCF is based on the well known Carrier Sensing Multiple Access with Collision Avoidance (CSMA-CA) mechanism. Before transmitting, each Wi-Fi node performs an assessment of the availability of the communication channel. This is known as the Clear Channel Assessment (CCA) which is described as follows. The node senses the channel and quantifies the power level of the potentially occurring communications. If this level exceeds a

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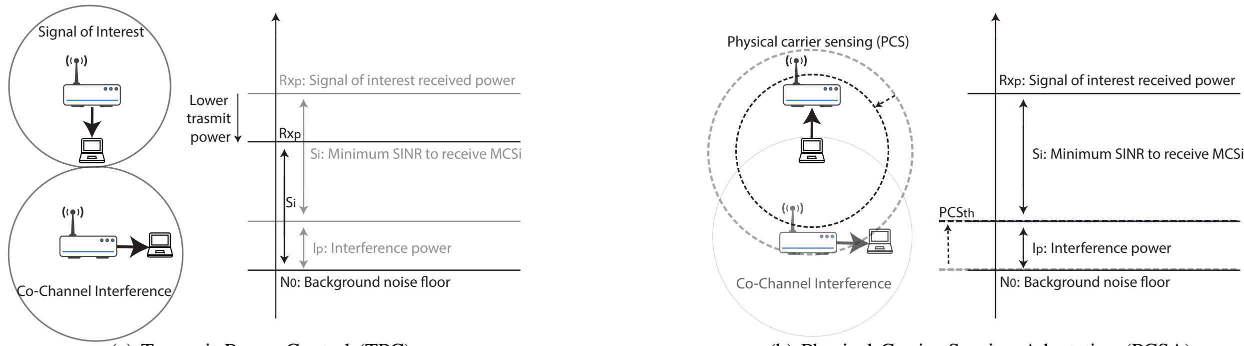


(a) Transmit Power Control (TPC) (b) Physical Carrier Sensing Adaptation (PCSA)

Fig. 1: Increasing spatial reuse using Transmit power Control (TPC) and Physical Carrier Sensing Adaptation (PCSA)

predefined threshold, the node treats the channel as busy and postpones its transmission. When the channel is detected as idle again, the node starts a random backoff countdown. The pending transmission starts directly after this backoff.

As described above, DCF is designed as a simple contention-based access scheme in the aim of distributing the available spectrum resources fairly among contending nodes. Authors in [6] show that the performance of DCF decreases exponentially with the increasing number of contending nodes. There are many research efforts to ameliorate the DCF performance by improving the backoff procedure parameters. One of the promising ideas is the *Optimal DCF* proposed in [7] where the product of the contention window (CW) and the transmission length is set to be proportional to the traffic load differential.

Although adapting the backoff procedure is important to ameliorate the performance of DCF in dense environments, Wi-Fi networks will not benefit from this amelioration if the carrier sensing and transmit power are not optimized. Actually, the latter parameters dictate the amount of interference incurred by the neighboring nodes. This means that an unoptimized carrier sensing and transmit power control mechanisms may mislead the *Optimal DCF* because they occur prior to any backoff procedure. On another hand, solutions like the *Optimal DCF* target the enhancement of DCF in the time domain and do not cope with the spectral efficiency of this access mechanism.

Currently, Wi-Fi operates in unlicensed frequency bands, namely 2.4 GHz and 5 GHz. The number of orthogonal channels available for this operation is limited. Thus, in infrastructure-based high density deployments, having co-channel Overlapping Basic Service Sets (OBSSs) is inevitable. The frequency channel is shared between the nodes in the overlapping region. Hence, in this region, due to the CCA mechanism described above, only one node transmits at a given instance and consequently the area throughput is degraded. To increase the spatial reuse the following solutions are envisioned.

A. Transmit Power Control

Inspired by the Transmit Power Control (TPC) schemes adopted in the cellular world [8] [9], many researchers proposed to reduce the transmission power of Wi-Fi transmitters in order to shrink the coverage of the neighboring BSSs to mitigate the co-channel OBSSs (see Fig. 1a). Therefore, many efforts were made to define adaptive transmit power for WLANs [10]. Furthermore, the IEEE 802.11h [11] standardized a TPC procedure to satisfy the regulation of maximum transmission power in the 5 GHz band in Europe.

However, in spite of the usage of the TPC to protect the satellite services, in the majority of the operating Wi-Fi networks today, all the nodes transmit at their maximum power. The main reason behind this behavior is that the TPC is a disincentive to the nodes applying it when there is no full compliance between all neighboring nodes. For instance, if only one AP decreases its transmission power, it will lose the opportunity to access the channel since it will be dominated by the surrounding co-channel APs transmitting at higher power.

In conventional Wi-Fi networks, the compliance of all the neighboring BSSs is impossible since their deployment is totally unplanned. Moreover, if a managed enterprise network applies the TPC, the presence of a minority of legacy devices severely degrades the overall performance of the network. Authors in [12] and [13] show that in the presence of several legacy devices in a high density network applying TPC results in up to 35% of aggregate throughput degradation. This is one of the major drawbacks of applying the TPC in Wi-Fi networks that are characterized by their contention-based MAC and unplanned deployments.

B. Physical Carrier Sensing Adaptation

The Physical Carrier Sensing Adaptation (PCSA) is presented as an alternative to the TPC that is able to achieve the same or better performance in some use cases. As shown in Fig. 1b, to overcome a co-channel OBSS situation, the PCS threshold (PCS_{th}) is increased. This adaptation mitigates the overlapped area, and as a result, the co-channel interference does not block anymore the transmissions of the node applying the PCSA. Consequently, more simultaneous transmissions are permitted and the spatial reuse is enhanced resulting in an improved aggregate throughput.

In contrast to the TPC, the PCSA benefits directly the node applying it, since this node will be able to transmit simultaneously with the ongoing communications. This is of key importance for Wi-Fi as its contention-based nature needs a sort of aggressiveness to guarantee a fair access to the medium. This becomes more essential in high density deployments where the OBSS problem is more common. The preceding incites Wi-Fi networks to adopt the PCSA in order to achieve better spatial reuse to satisfy the increasing demand.

In the presence of legacy devices, the PCSA overall performance does not suffer from serious degradation. A detailed study evaluating separately the TPC and the PCSA is conducted in [12] and [13]. In particularly, it has been shown in [13] that the aggregate throughput decreases by 10% in the presence of the same number of legacy devices that resulted in 35% of degradation in the TPC scenario. To extend this previous study, we intend in the present work to improve the situation by preserving higher degree of fairness especially in presence of legacy devices in future super dense environments. In the rest of the paper, a new approach that combines the PCSA and the TPC is proposed and shows its effectiveness in different scenarios.

III. Related SINR Expression

Depending on the transmission data rate, a communication is sustained only if the corresponding Signal to Interference and Noise Ratio (SINR) at the receiver exceeds certain mandatory value. Let S_i be the minimum required SINR for a Modulation and Coding Scheme (MCS) of index i, namely MCS_i. The achieved SINR is expressed by

$$SINR = \frac{Rx_p}{N_0 + I_P} \tag{1}$$

where Rx_p is the received power, N_0 is the background noise and I_p is the interference power at the receiver. All the previous power levels are expressed in watt (W) here. The received power is a function of the transmission power Tx_p and the propagation distance d as defined in Eq. (2)

$$Rx_p = Tx_p \times d^{-\gamma} \tag{2}$$

where γ is the path loss exponent. For a successful reception, the following equation must be satisfied.

$$SINR \geq S_i \tag{3}$$

As shown in [13], the relation between the PCS_{th} and the reception power Rx_p is expressed in its linear form as follows.

$$\frac{Rx_p}{PCS_{th}} = \left(1 + S_i^{\frac{1}{\gamma}}\right)^{\gamma} \tag{4}$$

Accordingly, the SINR can be expressed by:

$$S_i = \left(\left(\frac{Rx_p}{PCS_{th}}\right)^{\frac{1}{\gamma}} - 1\right)^{\gamma} \tag{5}$$

and making use of Eq. (2) and (5), we get the following.

$$S_i = \left(\frac{1}{d}\left(\frac{Tx_p}{PCS_{th}}\right)^{\frac{1}{\gamma}} - 1\right)^{\gamma} \tag{6}$$

The above expression shows the reflection of the transmission power and the carrier sensing on the SINR. While, transmitting at higher power increases the signal to noise ratio, the same increase can be obtained by decreasing the carrier sensing threshold. This shows that the TPC and the PCSA affect similarly the achieved signal to noise ratio and consequently the resulting throughput. This is verified later in this work by the simulation results.

IV. Proposed Balanced Transmit power control (TPC) and Physical carrier sensing (PCS) Adaptation (BTPA)

As explained before, a conventional Wi-Fi node transmits with the highest power. Yet, except for a minority of deployment scenarios, reduced transmission powers are sufficient

Fig. 2: Balanced Transmit power control (TPC) and Physical carrier sensing (PCS) Adaptation (BTPA) – the $ratio$

to achieve an SINR satisfying Eq. (3). Especially for short and medium transmitter-receiver distance where the S_i of the highest available MCS can be achieved with transmission powers much lower than the maximum power. Actually, when using the highest MCS, increasing the SINR more than the appropriate S_i will not bring important throughput gain. Thus in dense Wi-Fi environments, applying a TPC scheme increases the frequency reuse and decreases the energy consumption. For these reasons it is intuitive to reduce the transmission power when deploying high density Wi-Fi networks.

On another hand, when the co-channel BSSs are close to each other, if the PCS is not adapted, the transmitters will lose the possibility of simultaneous communications because of the overlapped areas where the STAs of one BSS are exposed to the communications occurring in a neighboring co-channel OBSS. Again, since the distance between the communicating nodes is short in dense networks, S_i is eventually satisfied despite the potential interference caused by co-channel simultaneous transmissions. Adapting the PCS is essential to enhance the reuse of the limited Wi-Fi frequency bands when super densifying is imminent.

Having in mind the above considerations, we propose in the sequel the Balanced TPC and PCS Adaptation (BTPA). Proceeding from the margin-based PCSA adaptation that we proposed in [13], every node calculates its PCS threshold in decibel scale as follows:

$$PCS_{th} = Rx_p - M \tag{7}$$

where M stands for the $margin$ parameter, a dB value defined for all the nodes of the given scenario and is related to the topology.

On the other side, we proposed in [13] the following TPC scheme. Every node reduces its transmission power so that its signal is received at a $margin$ (M) above the default minimum sensitivity threshold $PCS_{default}$ (-82 dBm in the case of 20 MHz bandwidth).

Let Δ_X be the difference between the traditional sensitivity $PCS_{default}$ and the adapted PCS_{th} as expressed below:

$$\Delta_X = Rx_p - M - PCS_{default} \tag{8}$$

According to the PCSA, the PCS_{th} is increased by Δ_X to adapt the carrier sensing mechanism. Instead of that, in the BTPA, Δ_X is used to adapt both the carrier sensing and the transmission power. Accordingly, the PCS_{th} will be increased by Δ_{PCS} dB and the transmission power will be decreased by Δ_{TPC} dB. The following equations show how the values of Δ_{PCS} and Δ_{TPC} are calculated using the $ratio$.

$$\Delta_X = \Delta_{PCS} + \Delta_{TPC} \tag{9}$$

$$\Delta_{TPC} = ratio \times \Delta_X \tag{10}$$

As depicted in Fig. 2, a $ratio$ equal to 0 means no TPC, i.e. the PCS is increased by Δ_X. Increasing the $ratio$ means

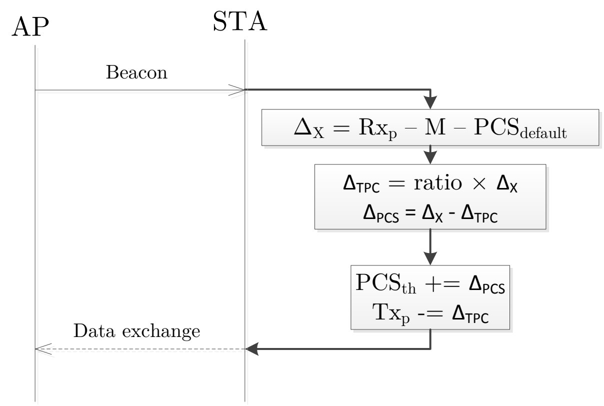


Fig. 3: Balanced Transmit power control (TPC) and Physical carrier sensing (PCS) Adaptation (BTPA) – an example

introducing more and more TPC. If the $ratio$ is set to 1, the Δ_{TPC} value would be equal to Δ_X and the node performs only a TPC without PCSA. This rule is proposed in order that each mechanism (PCSA and TPC) counteracts the unfairness of the other mechanism.

For a simple scenario, the application of the BTPA is illustrated in Fig. 3. In this toy example, a new STA associates to an existing BSS and starts a new communication with its AP. Upon the reception of a beacon frame from the AP, the STA calculates Δ_X value. From an implementation point of view, it is simple to broadcast the $ratio$ value in the beacon frame itself. Knowing the $ratio$, the STA deduces the values of Δ_{PCS} and Δ_{TPC}. The last step is to calculate the new carrier sensing threshold (PCS_{th}) and transmission power (Tx_p) parameters and apply them before proceeding to the intended data exchange.

V. Evaluation

To simulate the fairness problem and evaluate the proposed solution, OPNET modeler [14] is used in this work. OPNET is a well-known packet level simulator widely used in the literature. A high density cellular deployment is considered as depicted in Fig. 4. All the shown BSSs operate on the same frequency channel. Each BSS has 8 stations (STAs) associated to their AP placed at the center of an hexagon of 7 meters. The distance between two co-channel APs is 21 meters, i.e. a frequency reuse of 3 is considered.

Table I presents a summary of the main simulation system parameters. All the simulated nodes implement the IEEE 802.11n MAC and PHY, operate in 20 MHz band and have only one spatial stream (i.e. one antenna). A UDP full buffer traffic generator is configured on all nodes. The default transmission power is 15 dBm and the default PCS threshold is as defined by the standard for 20 MHz bandwidth, -82 dBm. For all the adaptation mechanisms we chose the same $margin$ value as in [13], i.e. $M = 20$ dB.

A. Performance comparison

In this section, we compare the performance in terms of throughput fairness of five different modes: no adaptation (applying default settings), the best fixed PCS threshold, the PCSA, the TPC, and the proposed BTPA. The first mode serves as a reference and reflects the conventional Wi-Fi

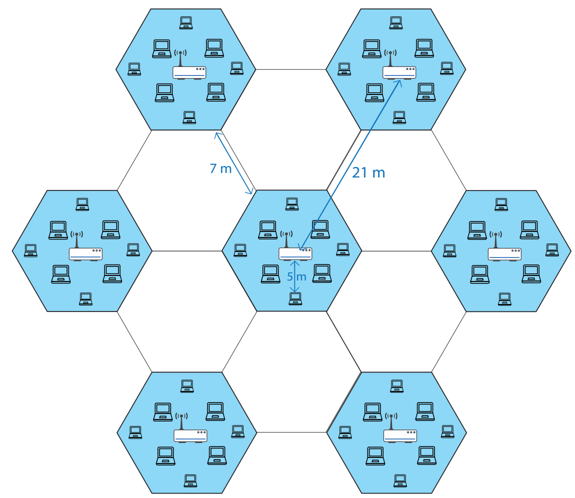


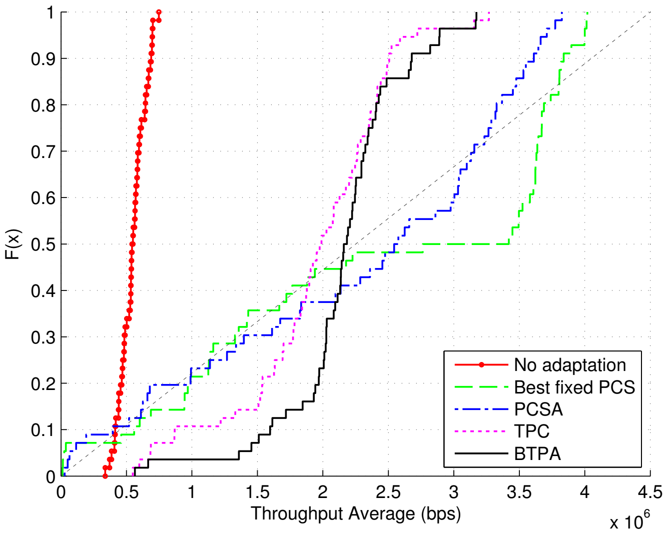
Fig. 4: Dense network topology

deployments today. For the BTPA, we consider a $ratio$ of 0.5 to carry out this comparison. Later in this work, we study the value of the $ratio$ in terms of the number of legacy nodes. After running the same simulation scenario for the different adaptation mechanisms, the Cumulative Distribution Function (CDF) of the average individual throughputs achieved by all the STAs is calculated. The slope of the CDF curve is a good indication of fairness. The more the slope is positively steep, the more fairly the throughput is distributed among nodes.

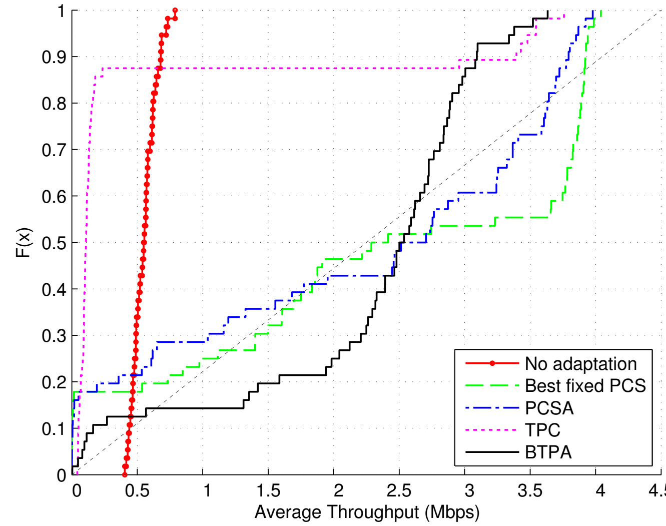
For all the conducted simulations, we consider two cases: the first does not include any legacy node (all the nodes are able to apply the corresponding adaptation scheme); the second consists of configuring one legacy STA per BSS (this STA applies the default carrier sensing and transmission power parameters). In the latter case, the number of legacy STAs represents 12.5% of the total number of STAs. The CDFs of the first and the second case are plotted respectively in Fig. 5a and 5b and represented by the function $F(X)$. In the sequel, the non-legacy STAs are called 802.11ax STAs.

1) In the absence of any legacy node: the unfairness is caused by the asymmetry of the communication links. This asymmetry is linked to the fact that different nodes may have different carrier sensing and transmission power parameters. This can be clearly seen in Fig. 5a when looking to the CDF of the no adaptation mode where the parameters are set to their default values, and hence are the same for all the nodes. It is true that the best fairness (the steepest slope) is achieved by this mode, but the aggregate throughput is the lowest as depicted in Table II for case (a). This is due to the lack of spatial reuse and the related OBSS problem. As detailed before, the traditional carrier sensing and transmission power parameters are over-conservative and prevent possible concurrent transmissions.

It is worth noting here that the proposed mechanism (i.e. BTPA) achieves the best performance among the other adaptation modes since it is able to preserve the highest degree of fairness all in accomplishing high aggregate throughput. As shown in Table II for case (a), the highest aggregate throughputs are achieved by the best fixed PCS and the PCSA modes. That is caused by the symmetry ensured by the fixed PCS configuration (all the nodes having the same PCS_{th} and Tx_p), on one hand, and the non optimal BTPA $ratio$ chosen for this part of the simulations (0.5), on the other. However,



(a) Without legacy STAs



(b) With legacy STAs (12.5% of total STAs)

Fig. 5: Average throughput performance comparison: Transmit Power Control (TPC), Physical Carrier Sensing Adaptation (PCSA), Balanced TPC and PCS Adaptation (BTPA), Best fixed PCS, and no adaptation

TABLE I: Simulation parameters

Parameter	Value
MAC & PHY	802.11n
Radio band	5 GHz
Bandwidth	20 MHz
Guard Interval (GI)	Short (400 ns)
Number of antennas for each node	1
Aggregate MAC Service Data Unit (A-MSDU) max size	3839 Bytes
Aggregate MAC Protocol Data Unit (A-MPDU) max size	8191 Bytes
UDP traffic	full buffer
Default Transmit power	15 dBm
Default physical carrier sensing threshold (PCS_{th})	-82 dBm
Simulation Duration	3 min

TABLE II: Aggregate throughputs

Mode	No adaptation	Best fixed PCS	PCSA	TPC	BTPA
Aggregate throughput (Mbps)	(a)30.69 (b)30.69	(a)136.3 (b)132.1	(a)125.6 (b)120.8	(a)108.5 (b)29.19	(a)120.6 (b)128.2

these highest aggregate throughputs are obtained in detriment of the fairness performance clearly identified when comparing the corresponding curves' slopes with that of the BTPA (see Fig. 5a). As argued earlier in this paper, when there's full compliance, TPC achieves good performance. This is why TPC, in absence of legacy nodes, approaches the BTPA in terms of performance as shown in Fig. 5a.

2) In the presence of legacy nodes: all the adaptation modes are challenged. The worst performance is that of TPC as shown clearly in Fig. 5b and Table II for case (b). As discussed before, the legacy STAs (12.5% of STAs) using the highest power cause the starvation of the 802.11ax STAs (86% of STAs). As a consequence, the average throughput achieved using TPC is marginal for $F(X) \leq 0.86$ as depicted in Fig. 5b. It is clear now why device manufacturers and network administrators are not considering a widespread TPC application. At the contrary of the TPC that favors legacy nodes, adapting the carrier sensing favors the 802.11ax nodes. Consequently, the performance of the best fixed PCS and the PCSA is slightly harmed as the slopes of their corresponding $F(X)$ curves are less steep in Fig. 5b and their aggregate throughput is decreased as recorded in Table II for case (b).

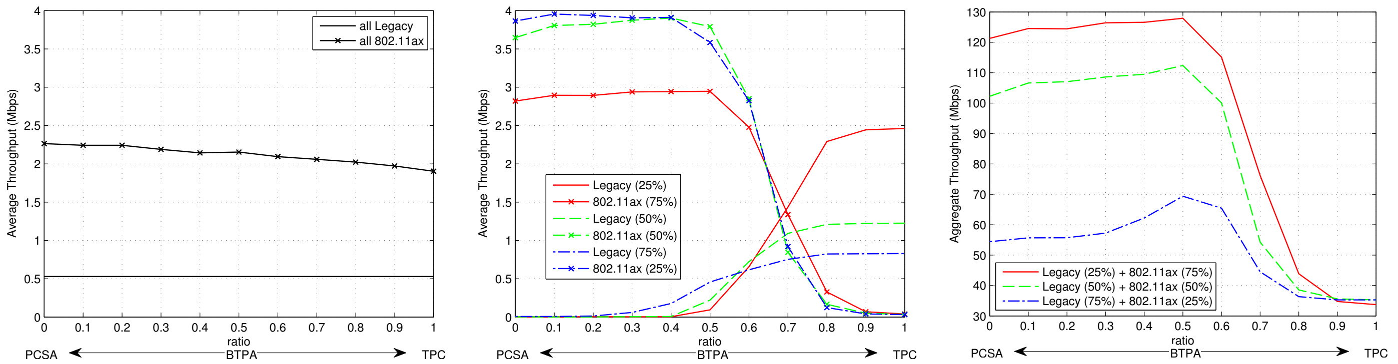
Again, the best performance is achieved by the BTPA. In spite of the presence of the legacy devices, our proposal is able to achieve a high aggregate throughput with the best degree of fairness. Oddly, comparing to case (a), the aggregate throughput achieved by the BTPA is higher in case (b) where 12.5% of STAs are legacy. This is due to the non optimal $ratio$ value assumed in this part of the simulations leading to less airtime share for legacy STAs (as shown when $F(X) \leq 0.14$), and hence more throughput achieved by the remaining 86% of STAs (802.11ax STAs). This brings to light the importance of an optimal BTPA $ratio$ for better fairness between different nodes.

B. Ratio value in presence of legacy devices

Choosing the value of the $ratio$ may depend on multiple factors. In this section, we examine the effect of the number of legacy nodes present in the network on the optimal $ratio$ value. For this purpose, the simulation is run for different $ratio$ values ranging from 0 to 1 as depicted in Fig. 2. The BTPA is applied as described by equations (9) and (10).

As a reference, Fig. 6a compares, in terms of average throughput, two independent simulation configurations: the *all legacy* where all the nodes apply the default settings as in conventional networks (i.e. no BTPA); and the *all 802.11ax* where all the nodes apply the BTPA. For the latter, the ratio is varied from 0 (PCSA only) to 1 (TPC only). This comparison shows the important gain in average throughput achieved by the proposal. For instance, the average throughput increases from 0.5 Mbps to 2.15 Mbps for $ratio = 0.5$ (i.e. more than $4X$). The average throughput achieved by applying the BTPA on all the nodes (i.e. *all 802.11ax* configuration) is quite stable but slightly better with lower ratio as shown in Fig. 6a. This stability affirms the previous analysis made in Section III where we argued that the TPC and the PCSA equally affect the SINR and hence the achieved throughput.

To bring to light the effect of the presence of legacy STAs



(a) All legacy versus all 802.11ax (b) Legacy and 802.11ax - Average Throughput (c) Legacy and 802.11ax - Aggregate Throughput

Fig. 6: Throughput performance in terms of the $ratio$ of the BTPA in presence of legacy nodes

in the network on the optimal BTPA $ratio$, we consider three configurations with different proportions of legacy STAs. In the first configuration 25% of STAs are legacy, in the second 50% are legacy, and in the third 75% of STAs are legacy. The corresponding results are presented in Fig. 6b where the average throughput achieved by the legacy STAs is separated from that achieved by the 802.11ax STAs. Accordingly, for each of the three configurations we have two average throughput curves respectively for the legacy and the 802.11ax STAs.

For all of the three configurations, when the BTPA $ratio$ is below 0.5 the average throughput achieved by the 802.11ax STAs is quite stable at its maximum attained level. Yet, the legacy STAs are almost not able to transmit for these values of BTPA $ratio$. This observation is reasonable recalling the fact that PCSA favors the 802.11ax nodes. Increasing the $ratio$ above 0.5 increases the average throughput achieved by the legacy STAs. Normally, in ordinary situations where the coexistence is unavoidable, fairness means aiming at equitable throughput for all nodes whether they are legacy or not. The results in Fig. 6b show that BTPA is able to achieve this fairness for any proportion of legacy devices. For instance, for the simulated scenario, for a $ratio$ around 0.7, the averaged throughputs achieved by all the nodes are very close.

Although the main aim of the proposed BTPA is to enhance the fairness among nodes particularly in presence of legacy STAs, the aggregate throughput must be maintained at high values to fully benefit from the intended gain in spatial reuse. Fig. 6c shows the aggregate throughput achieved by each of the previous three configurations. The $ratio$ should be chosen so as to maximize the aggregate throughput (i.e. as close as possible to 0.5) while ensuring the best possible fairness in average throughput. For our scenario a $ratio \simeq 0.65$ allows a good trade-off to reach the previous objectives.

VI. Conclusion

In future super dense Wi-Fi deployments, the contention-based access mechanism defined in the IEEE 802.11 standard by the DCF is challenged. The same challenge will be faced by the envisioned operation of LTE on unlicensed bands. To attain the goal of the densification, i.e. increasing the system capacity, the spatial reuse needs to be leveraged. In this work, the envisioned carrier sensing and transmission power adaptation are questioned and their unfairness issues are highlighted. Furthermore, a balanced adaptation combining the two techniques is proposed and shows an outperforming fairness with fourfold increase in average throughput. Particularly, by optimizing the BTPA $ratio$ the same average throughput can be achieved by any STA for any number of legacy STAs present in the network. The BTPA approach could also be used for 3GPP LAA channel access protocol to cope with the coexistence of different technologies especially in dense environments.

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