ETP Algorithm: Increasing Spatial Reuse in Wireless LANs Dense Environment Using ETX

Tanguy Ropitault, Nada Golmie
NIST, 100 Bureau Dr., Gaithersburg, MD, USA
tanguy.ropitault@nist.gov, nada.golmie@nist.gov

***Abstract*—To address the issues related to the extreme densification of wireless networks, namely increased interference and lower overall throughput, the IEEE 802.11ax project was formed to revise the standard specifications for IEEE 802.11ac in order to increase the spectrum efficiency and most notably the per-user throughput by a factor of four. Improving Spatial Reuse (SR) is seen as one of the main techniques for achieving this goal.**

In this paper, we explore the so-called Overlap Basic Service Set Physical Detection (OBSS_PD)-based SR technique introduced in IEEE 802.11ax, which aims to increase SR by adapting both stations' Carrier Sensitivity Threshold (CST) and transmission power. To that end, OBSS_PD PD-based SR defines a proportional relationship between CST and the transmission power. In this article, we propose a novel and dynamic algorithm to implement an OBSS_PD PD-based SR. This so-called ETX To Power (ETP) algorithm uses the Expected Transmission Count (ETX) metric to dynamically compute the transmission power and the CST to use.

Simulations are used to evaluate ETP in a dense scenario. We show that the overall system throughput is improved by 40 % compared to IEEE 802.11 legacy networks and at the same time the 5th percentile throughput is also increased by 22 %.

I. Introduction

The Wireless Lan Network (WLAN) popularity in the last decade has led to a massive deployment of WLAN stations (STAs) and Access Points (APs). The IEEE 802.11 Task Group ax (TGax) is currently defining new specifications, which aim to tackle issues related to this densification by not only increasing overall system throughput but also per-station throughput. While several techniques may be envisaged to reach this goal, one of the most promising techniques is based on Spatial Reuse (SR) improvement. SR improvement focuses on increasing the number of successful concurrent transmissions in the network. As shown in [1] and [2], two main methods can enable SR improvement: Carrier Sense Threshold (CST) tuning and Transmit Power Control (TPC). CST tuning operates by adjusting the CST in order to reduce the carrier sensing range, allowing more concurrent transmissions. On the other hand, TPC aims at improving SR by reducing the transmission power and thus the level of generated interference.

CST tuning and TPC have already been extensively studied in the past. For example, [3], [4], and [5] reveal the significant impact of CST tuning on throughput while [6], [7], and [8] demonstrate the benefits of TPC on throughput in dense environments. However, these studies only use one of the possible methods to increase SR. Few studies have been conducted on combining both TPC and CST. Roslan et al. propose a new method to tune both transmission power and CST [9]. While the authors show big improvements regarding throughput and fairness, the usage of a bloom filter to determine the Basic Service Set (BSS) of a frame imposes implementation changes to every device. Yang et al. introduce an algorithm to determine both the transmit power and the carrier sense of a node [10]. 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.

The OBSS_PD-based SR, proposed at TGax also uses both CST tuning and TPC to increase SR [11]. In dense deployments, due to the limited number of available channels, several BSSs are going to operate on the same channel, leading to Overlapping BSS (OBSS). The challenge when it comes to SR improvement is to reduce as much as possible the influence of each OBSS on each other. Regarding CST tuning, OBSS_PD-based SR uses two different CSTs: the legacy one and a new CST threshold called $OBSS\_PD_{Thr}$. The former is used to sense intra-BSS frames, i.e., frames coming from the BSS on which the STA is associated while the latter is utilized to sense inter-BSS frames i.e., frames coming from OBSSs. $OBSS\_PD_{Thr}$ is generally higher than the legacy one in order to reduce the sensing range for the other OBSSs and enable more concurrent transmissions. In order to combine CST tuning and TPC, OBSS_PD-based SR defines a proportional relationship between the transmission power (*TXPWR*) and the $OBSS\_PD_{Thr}$. When the $OBSS\_PD_{Thr}$ is increasing (i.e., reducing its sensing range for OBSSs), the *TXPWR* is reduced (i.e., lowering the interference level in the network) and vice versa.

While OBSS_PD-based SR defines the framework to increase SR, it does not give any specific details on how to use it. Indeed, in order to exploit the defined proportional relationship, one parameter's value, either *TXPWR* or $OBSS\_PD_{Thr}$ is needed, and the way to obtain it is left open to implementation/vendors. No matter the chosen value (*TXPWR* or $OBSS\_PD_{Thr}$), it should be dynamically computed and adapted to reflect current network conditions. This property must allow a given STA to evaluate if it should try to participate in the SR improvements when the network conditions are favorable or on the contrary, to follow a more conservative approach. At the end, the SR improvement is the result of all STAs behaviors. One STA increasing its $OBSS\_PD_{Thr}$ will reduce its sensing range for inter-BSS frames and therefore will have more transmission opportunities, which in turn could prevent other STAs from transmitting.

In this paper, we propose the ETX To Power (ETP) algorithm which computes the *TXPWR* using the Expected Transmission Count (ETX) value. Once computed, the *TXPWR* value is fed to the OBSS_PD-based SR to derive the $OBSS\_PD_{Thr}$ value. The ETX metric varies dynamically with the network conditions for a given STA, increasing whenever the number of frame transmissions is higher than the previous one and vice versa. It is worth mentioning that using the ETX metric does not impose any hardware or standard modifications and requires only the monitoring of the number of retransmissions. We evaluate the ETP performance using a simulation of the enterprise scenario, a dense scenario proposed in the TGax simulation scenarios document [12].

The remainder of the paper is organized as follows. Section II introduces the OBSS_PD-based SR solution and the ETX metric. Section III outlines the ETP algorithm and Section IV describes the scenario and parameters used to evaluate ETP. Section V presents the results and Section VI offers concluding remarks and potential future extensions.

II. Background

This section introduces the OBSS_PD-based SR technique and the ETX metric used by the ETP algorithm described in Section III.

A. OBSS_PD-based SR

As seen in Section I, OBSS_PD-based SR introduces a new CST, $OBSS\_PD_{Thr}$, used for inter BSS frames and proportional to the *TXPWR*.

To identify if a frame is intra or inter BSS, BSS coloring is used. BSS coloring, introduced in IEEE 802.11ah [13], consists of BSS nodes inserting a new field called "BSS color" in the preamble of every 802.11 frame. The originator of the BSS color field is the AP itself and each BSS has a different color, allowing a STA to decode the preamble and determine which BSS the frame is coming from.

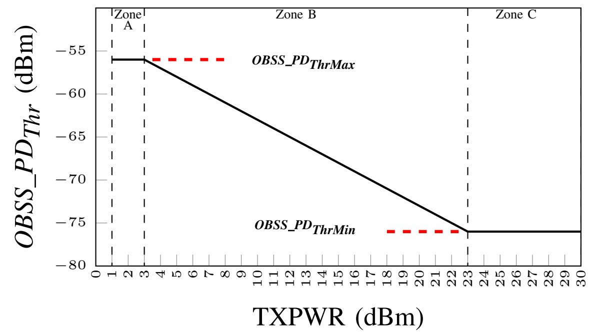


Figure 1: Relationship between *TXPWR* and $OBSS\_PD_{Thr}$ for a 80 MHz bandwidth.

$OBSS\_PD_{Thr}$ is computed using (1), where $OBSS\_PD_{ThrMin}$ and $OBSS\_PD_{ThrMax}$ are the minimum and maximum possible values for $OBSS\_PD_{Thr}$.

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

$OBSS\_PD_{ThrMin}$ and $OBSS\_PD_{ThrMax}$ are set by default to -82 dBm and -62 dBm for a 20 MHz bandwidth in the OBSS_PD-based SR document [11]. $TXPWR_{ref}$ is the reference transmission power and *TXPWR* is the actual transmission power. $TXPWR_{ref}$ is set by default to 23 dBm. To compute $OBSS\_PD_{ThrMin}$ and $OBSS\_PD_{ThrMax}$ for a different bandwidth, (2) and (3) are used.

$$OBSS\_PD_{ThrMin} = OBSS\_PD_{ThrMin}(20\ MHz) + 10 \cdot log\left(\frac{Bandwidth}{20\ MHz}\right) \quad (2)$$

$$OBSS\_PD_{ThrMax} = OBSS\_PD_{ThrMax}(20\ MHz) + 10 \cdot log\left(\frac{Bandwidth}{20\ MHz}\right) \quad (3)$$

In this paper, we evaluate the performance of $OBSS\_PD_{Thr}$ in 80 MHz as recommended in the simulation scenarios defined by TGax [12]. Thus, $OBSS\_PD_{ThrMin}$ and $OBSS\_PD_{ThrMax}$ have a value of -76 dBm and -56 dBm respectively.

Figure 1 illustrates the relationship between *TXPWR* and $OBSS\_PD_{Thr}$ as defined in (1), for power varying between 1 dBm and 30 dBm for a 80 MHz bandwitdh. Three zones, A, B, and C are observed as highlighted on Figure 1. Zone A (between 1 dBm and 3 dBm) corresponds to the case where the *TXPWR* 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 high $OBSS\_PD_{Thr}$ reduces the sensing range of the 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 higher is the transmission power, the smaller is the $OBSS\_PD_{Thr}$. Finally, zone C (after 23 dBm) corresponds to the case where the *TXPWR* 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. $OBSS\_PD_{Thr}$ 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.

In order to implement OBSS_PD-based SR, we compute first the *TXPWR* based on the ETX value (using ETP algorithm described in Section III), and afterwards apply (1) to derive the $OBSS\_PD_{Thr}$.

B. ETX

ETX is a path quality metric extensively used in wireless networks. It represents the number of transmissions an STA expects to make in order to successfully transmit to a destination. ETX has the property to estimate the link condition by increasing whenever the number of transmissions needed to transmit a new frame is bigger than the previous frame and vice versa. ETX has been first introduced in [14] and is defined by (4), where df is the forward delivery ratio i.e., the measured probability that a data packet is successfully delivered to the receiver and dr is the reverse delivery ratio i.e, the probability that the acknowledgment packet is successfully received.

$$ETX = \frac{1}{df \cdot dr} \tag{4}$$

To measure df and dr, the authors use a dedicated link probe packets. Each node broadcasts fixed size link probes every τ period. This allows a precise characterization of df and dr but requires additional signaling and the implementation of a process in charge to keep track of df and dr every τ period.

To alleviate the aforementioned problem, we use an alternative ETX definition used mainly in wireless sensor networks and introduced for the first time in the Contiki Operating System implementation [15]. Contiki's implementation computes ETX using an exponentially weighted moving average filter as shown in (5), where $\alpha \in (0, 1]$ is a coefficient representing the degree of weighting decrease, ETX_{n-1} is the previously recorded ETX measurement and *NT* is the number of transmissions that has been needed to transmit the current frame. The *NT* value is increased each time a transmission/retransmission is performed for a given frame until the corresponding acknowledgment is received or that the maximum number of retransmissions is reached.

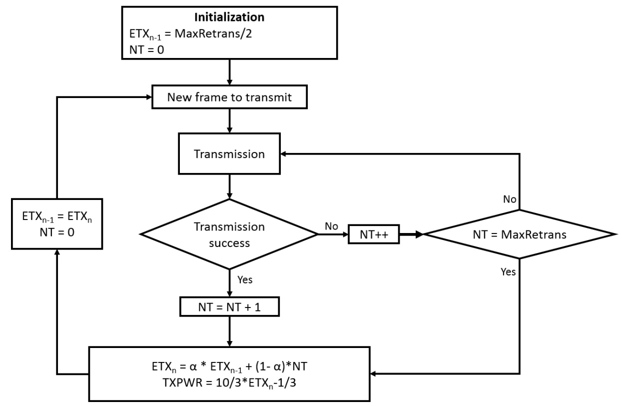


Figure 2: Flow chart of ETP algorithm

$$ETX_n = \alpha \cdot ETX_{n-1} + (1 - \alpha) \cdot NT \tag{5}$$

This ETX definition should be easy to implement as it only requires information about the number of transmissions and the previous ETX measurement. Note that α is critical as it defines the behavior of the system. The larger α is, the more significant ETX_{n-1} is.

III. ETP ALGORITHM

The ETP algorithm provides the OBSS_PD-based SR the *TXPWR* to use. To that end, ETP converts ETX to *TXPWR* values. The relationship between ETX and *TXPWR* is defined in (6) where a and b are chosen to represent the desired behavior of the system.

$$TXPWR(ETX) = a \cdot ETX + b \tag{6}$$

We define the minimum transmission power $TXPWR_{min}$ as the highest transmission power giving the maximum $OBSS\_PD_{Thr}$ ($OBSS\_PD_{ThrMax}$), i.e., $TXPWR_{min}$ = 3 dBm (see Figure 1). Similarly, we define the maximum transmission power $TXPWR_{max}$ as the lowest transmission power giving the minimum $OBSS\_PD_{Thr}$ ($OBSS\_PD_{ThrMin}$), i.e., $TXPWR_{max}$ = 23 dBm (see Figure 1). The ETX value, representing the number of retransmissions, is bounded i.e., ETX $\in [ETX_{min}, ETX_{max}]$. The minimum value ETX_{min}, representing a successful transmission, is $ETX_{min} = 1$ while the maximum value ETX_{max} representing the maximum number of retransmissions attempts, *MaxRetrans*, is implementation dependent. $ETX_{max} = 7$ as defined in the ns-3 simulator used for the evaluation. Having an $ETX = ETX_{min}$ means network favorable conditions for the STA which can thus seek for the maximum possible SR improvements by applying $TXPWR_{min}$. Similarly, having an ETX of ETX_{max} implies that the transmitting STA is experiencing very bad network conditions and should not seek SR improvements and use $TXPWR_{max}$. Solving (6) by knowing that $TXPWR(1) = 3$ dBm

Table I: Physical and MAC layer parameters

Parameters	Values	Parameters	Values
IEEE standard	802.11ac	MCS	5
Bandwidth	80 MHz	Propagation Loss	Log-distance 2 exponents
Traffic Type	Uplink UDP CBR	Wall Loss	7 dB
MPDU size	1538 bytes	Guard Interval	Short
Aggregation	32 MPDUs	α	[0:0.9]
STA Max TX Power	15 dBm	Simulated time	10 s
AP TX Power	20 dBm	Runs	40/α value

and $TXPWR(7) = 23$ dBm gives the parameter values $a = 10/3$ and $b = -1/3$.

The ETP algorithm is described in the flow chart presented in Figure 2. The initialization phase sets the number of transmissions *NT* to zero while the initial previously recorded ETX value $ETX_{n\text{-}1}$ is set to half of MaxRetrans i.e., 3.5 in order to allow each STA to starts with a moderate ETX value. When a transmission starts, *NT* is incremented for each transmission/retransmission. After a successful transmission or if the MaxRetrans is reached, the new ETX value ETX_n is computed and ETX is turned into a *TXPWR* value, used for the STA next transmission and fed to OBSS_PD-based SR to derive the $OBSS\_PD_{Thr}$ to apply. Finally, for the next transmission, $ETX_{n\text{-}1}$ is set to ETX_n while *NT* is set to 0.

IV. Simulation Setup

To evalute the ETP performance, we use the enterprise scenario described in the TGax simulation scenarios document [12]. This scenario is adequate in term of SR study as it represents a high density deployment comprising a large number of STAs (2048) and APs (32) in a small area (40 m x 80 m).

Figure 3 depicts the enterprise scenario. The topology is made of 8 offices separated by walls, each office being made 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 channels are assigned to the four APs of each office and each AP manages 16 cubicles i.e., 64 STAs are connected to each AP.

Table I presents the parameters used for the simulations conducted using ns-3 simulator [16]. Each STA sends UDP CBR traffic to its AP in order to saturate the medium using a MCS of 5 (around 200 Mbit/s). STA maximum transmission power is set to 15 dBm as recommended in [12]. ETP algorithm is configured with α values varying from $[0 : 0.9]$ with a step of 0.1.

Analyzing what goes on in a dense SR based scenario may be challenging given the complex interactions. While the aggregate throughput of all BSSs (total number of bytes received successfully by APs per second) is a good indicator, it cannot be the only one to consider. Indeed, SR improvements can increase aggregate throughput by increasing dramatically only some STAs throughput while others starve. Thus, we also investigate the 5th percentile throughput per-STA (average number of bytes successfully sent by the 5 % STAs exhibiting the worse throughput performances) and the fairness computed using the goodput ratio. The goodput ratio for a station i is expressed using (7).

$$GR_i = \frac{R_i}{T_i} \tag{7}$$

where R_i is the number of UDP packets correctly received by the AP on which a STA i is associated and T_i is the number of UDP packets generated by this station i. Moreover, in order to study α influences, we analyze the average ETX value per STA and the average time spent by each STA to transmit during the simulation.

V. Performance Evaluation

We evaluate the performance of the OBSS_PD-based SR ETP algorithm in the enterprise scenario. The case of legacy devices case i.e., devices using one fixed CST with $CST = -76$ dBm, is used as a baseline comparison.

Figure 4a represents the ETP algorithm aggregate throughput percentage increase compared to the legacy devices case. First, we can observe that OBSS_PD-based SR with ETP clearly outperforms the legacy devices case by producing an increase of aggregate throughput for every α value. We can also notice that α has a significant impact on the aggregate throughput. The aggregate

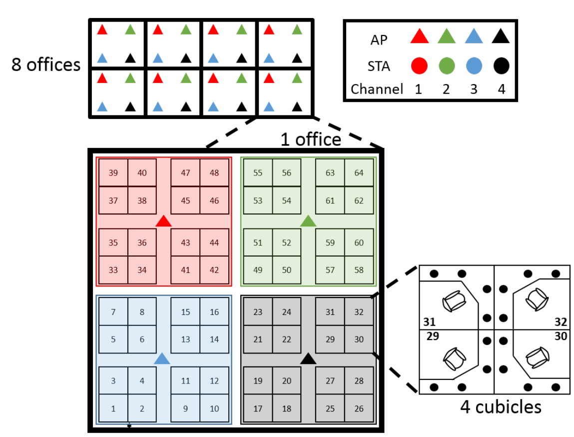
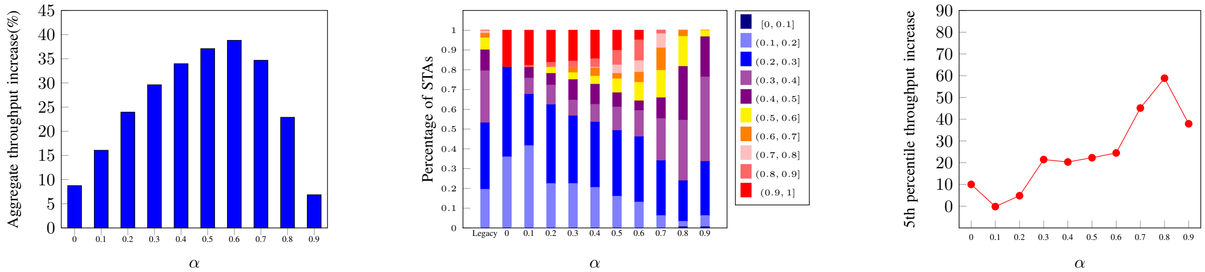


Figure 3: Enterprise scenario topology

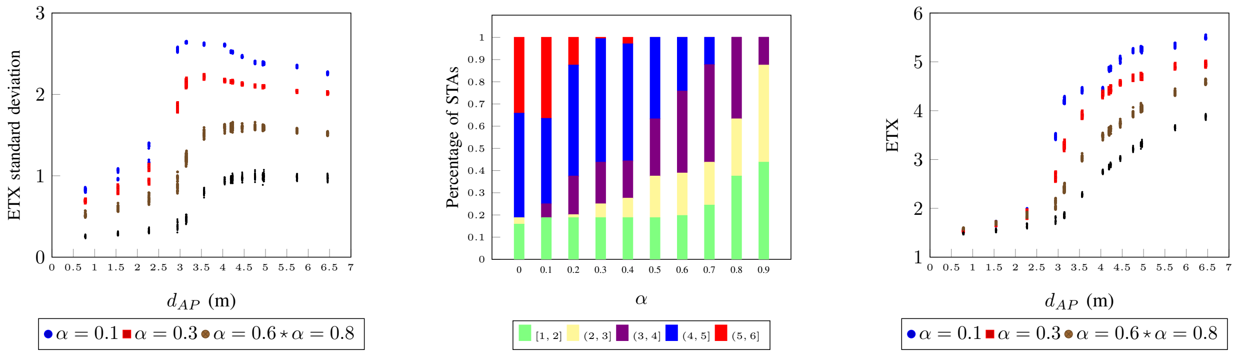


(a) Aggregate throughput percentage increase

(b) Goodput ratio distribution

(c) 5th percentile throughput percentage increase

Figure 4: Overall results metric



(a) ETX Standard deviation values vs. distance (d_{AP}). One point corresponds to the standard deviation for the average ETX of one STA.

(b) ETX distribution

(c) ETX value vs. distance (d_{AP}). One point corresponds to one STA ETX average value.

Figure 5: ETX results

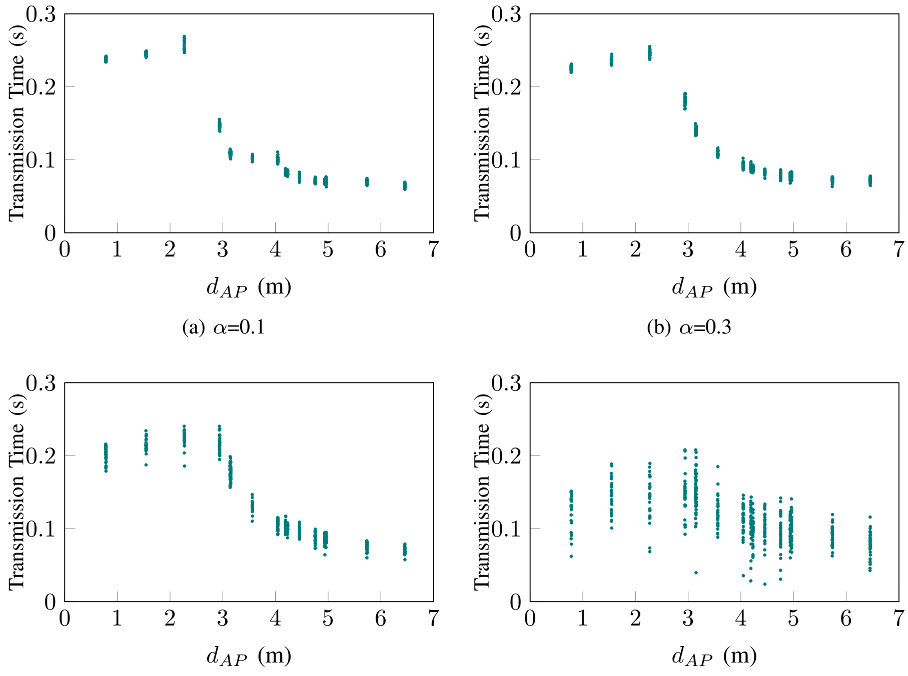
throughput grows with α and reaches its maximum for $\alpha = 0.6$, producing a 38 % improvement, before decreasing with higher α values.

Figure 4b shows the stacked distribution of the goodput ratio per STA depending on α. We can see that the obtained goodput ratio distribution also highly depends on α. With $\alpha = 0$, we observe the highest unfairness among STAs with 80 % of them experiencing a low goodput ratio (less than 0.3) while 20 % of STAs have a large goodput ratio (between 0.9 and 1). It means that while some STAs are able to perfectly send all their traffic, the vast majority of them experience a low datarate which is highly unfair. However, we notice that the larger α is, the fairer the system tends to be. We observe for example that the percentage of STAs experiencing the maximum goodput ratio (between 0.9 and 1) decreases with α until it reaches zero for $\alpha = 0.7$. The opposite applies for the percentage of STAs experiencing the worst throughput (between 0.1 and 0.2) which diminishes when α is increasing. Thus, increasing α tends to improve fairness among STAs.

Figure 4c shows the 5th percentile average throughput improvements compared to the legacy devices case. We can observe that all α values (except 0.1) gives an increase in the 5th percentile throughput with a maximum improvement of 60 % observed for $\alpha = 0.8$. ETP does not only increase the overall system throughput but also the throughput for the STAs experiencing the worst performances, reinforcing the fairness of the system and working towards TGax objectives.

To summarize, Figure 4 shows that ETP increases the aggregate throughput, fairness, and the 5th percentile throughput. However, the performance highly depends on α. The differences regarding the observed gains can be explained by the effects of α on the ETX value computation, and thus on the *TXPWR* and the $OBSS\_PD_{Thr}$ used by a STA. As shown in Section II, having a larger α leads to a more conservative and stable ETX computation and thus to more conservative *TXPWR* and $OBSS\_PD_{Thr}$ values. In case of sudden degradations/improvements of the network conditions (i.e., in term of number of retransmissions), *TXPWR* and $OBSS\_PD_{Thr}$ values are going to evolve slowly when α is large.

This is confirmed in Figure 5a where we show the standard deviation of the ETX value of each STA regarding to its distance to its AP (d_{AP}) for α values of 0.1, 0.3, 0.6, and 0.8. We chose these representative values for the remaining of our analyse in order to ease the readability of the figures, to have sufficient α values to observe the trend, and as they comprises the α values producing the highest aggregate throughput and the best 5th percentile throughput (0.6 and 0.8). It is worth mentioning that we limited our analysis to one channel (channel 1 on Figure 3 i.e., 512 STAs and 8 APs)



(a) α=0.1 (b) α=0.3 (c) α=0.6 (d) α=0.8

Figure 6: Total transmission time spent by each STA for channel 1. One point represents the time for one STA.

as there is no adjacent channel interference for 5 GHz channel. However, the observed trends were the same for every channel. We can see on Figure 5a that the larger is α, the smaller is the standard deviation for a given d_{AP}. It confirms that ETX value is more conservative when α is growing.

Figure 5b represents the stacked distribution of ETX value depending on α value. We can observe that the larger α is, the smaller is the percentage of STAs having the worst ETX values (between 4 and 6). We can also notice that the larger the α is, the larger is the percentage of STAs experimenting the best ETX value (between 1 and 3). When α increases, STAs are going to have in average smallest ETX value. Having a smaller ETX value leads STAs to participate more to SR improvement by assigning to STA: a smaller *TXPWR* value which reduces the interferences due to the transmission, and a highest $OBSS\_PD_{Thr}$, resulting in more transmission opportunities.

Figure 5c represents the average ETX for every STA related to d_{AP}. We can observe first in Figure 5c that ETX values are correlated with d_{AP}. The larger is d_{AP}, the bigger are the ETX values for a given α. We can additionally notice that for $d_{AP} < 2$ m , the ETX values are concentrated and almost identical (ETX comprises between 1 and 2) for any α. Finally, a major evolution is occurring for STAs which $d_{AP} \approx 3\ m$. The differences between every α group of ETX values is increasing suddenly and remains the same for $d_{AP} > 3\ m$. These observations indicate first that the closest STAs ETX values are not sensitive to α value. Then, it indicates that ETX is very sensitive to small differences in the topology as α values influence on ETX is magnified even for a little increase in distance. These trends are expected as ETX is directly related to the number of retransmissions. The larger is d_{AP} for a STA, the more difficult is the decoding of its transmission by its AP in case of multiple concurrent OBSS transmissions occurring in the network. The larger is α, the smaller these difficulties are going to be represented on the ETX values. However, we still have a counterintuitive result: we have seen that the larger is α, the smaller are the ETX values. Then, we would expect that the larger is α, the larger is the aggregated throughput as less retransmissions for every STA should mean a higher throughput for every STA.

Figure 6 represents the average total time spent by each STA to transmit depending on d_{AP}. If we compare the results for $\alpha = 0.1$, 0.3, and 0.6, we can see that the trend is the same: the larger is the distance, the less time the STA spent to transmit. However, we can observe that for a given distance, the larger is α, the more scattered are the total transmission time. More particularly, we can notice that for $d_{AP} < 2m$, the total time spent to transmit is decreased when α is increasing while the opposite occurs for STA with $d_{AP} > 2\ m$. This is due to the fact that the larger the α is, the smaller is in average the ETX computed for furthest away STAs, resulting in these STAs having a bigger $OBSS\_PD_{Thr}$ and thus having more transmission opportunities and letting less transmission opportunities for the closest STAs. For $\alpha = 0.8$, we can see a major evolution with the time spent by each STA being almost independent to its distance to its AP. STAs closest to the AP spend almost the same amount of time to transmit as does the furthest away STAs. The overall system has gone from a highly unfair state when $\alpha = 0$ to an equilibrium state when every STA has almost the same transmission opportunities when $\alpha = 0.8$. It explains why the α value of 0.8 produces the best 5th percentile throughput, each STA having the same transmission opportunities whatever is its distance. Finally, the aggregate throughput is not increasing with α when $\alpha > 0.6$ as the transmission time is decreased for STA with the smallest ETX to the benefits of STA with highest ETX, resulting in smallest aggregate throughput.

The achievable SR improvements is definitely related to the topology. Reducing/increasing *TXPWR* and $OBSS\_PD_{Thr}$ of some STAs can drastically change the system performances. However, ETP algorithm is able to increase aggregate throughput, fairness and 5th percentile STA throughput for the enterprise scenario which makes ETP a good candidate to implement for OBSS_PD-based SR. $\alpha = 0.6$ is the optimum value, producing an aggregate throughput and 5th percentile increase of respectively 38 % and 20 % compared to legacy only devices case.

VI. Conclusion

In this paper, we proposed and evaluate the ETP algorithm for an OBSS_PD-based SR solution defined in 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 ETP for OBSS_PD-based SR allows in the enterprise scenario to improve the throughput by 38 %, hence by a factor close to 1.4. However, for a maximum throughput increase, the fairness is not always guaranteed showing the tradeoff between maximum reachable throughput and fairness. Combining ETP for 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.

We proposed a first ETP OBSS_PD-based SR implementation by using the ETX metric. This method could be further refined by taking into account for example the RSSI of received beacons in order to have an estimation of the STA distance to its AP. It could allow ETP for OBSS_PD-based SR to react faster to sudden topology changes.

References

[1] B. Alawieh, Y. Zhang, C. Assi, and H. Mouftah, "Improving spatial reuse in multihop wireless networks - a survey," *IEEE Communications Surveys Tutorials*, vol. 11, no. 3, pp. 71–91, rd 2009.

[2] T. S. Kim, H. Lim, and J. C. Hou, "Understanding and improving the spatial reuse in multihop wireless networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 10, pp. 1200–1212, Oct 2008.

[3] J. Zhu, X. Guo, L. L. Yang, and W. S. Conner, "Leveraging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing," in *2004 IEEE International Conference on Communications*, vol. 7, June 2004, pp. 4004–4011 Vol.7.

[4] V. P. Mhatre and K. Papagiannaki, "Optimal design of high density 802.11 wlans," in *Proceedings of the 2006 ACM CoNEXT Conference*, 2006, pp. 8:1–8:12.

[5] E. Haghani, M. N. Krishnan, and A. Zakhor, "Adaptive carrier-sensing for throughput improvement in ieee 802.11 networks," in *2010 IEEE Global Telecommunications Conference*, Dec 2010, pp. 1–6.

[6] J. P. Monks, V. Bharghavan, and W. M. W. Hwu, "A power controlled multiple access protocol for wireless packet networks," in *20th Annual Joint Conference of the IEEE Computer and Communications Society*, vol. 1, 2001, pp. 219–228 vol.1.

[7] A. Muqattash and M. Krunz, "Power controlled dual channel (PCDC) medium access protocol for wireless ad hoc networks," in *22nd Annual IEEE Conference on Computer Communications*, vol. 1, March 2003, pp. 470–480 vol.1.

[8] ——, "A single-channel solution for transmission power control in wireless ad hoc networks," in *Proceedings of the 5th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, 2004, pp. 210–221.

[9] I. Roslan, T. Kawasaki, T. Nishiue, Y. Takaki, C. Ohta, and H. Tamaki, "Control of transmission power and carrier sense threshold to enhance throughput and fairness for dense wlans," in *2016 International Conference on Information Networking*, Jan 2016, pp. 51–56.

[10] Y. Yang, J. C. Hou, and L.-C. Kung, "Modeling of physical carrier sense in multi-hop wireless networks and its use in joint power control and carrier sense adjustment," in *26th Annual IEEE Conference on Computer Communications*, 2007.

[11] "Clarifications for OBSS_PDbased SR parameters," IEEE 802.11ax , IEEE 802.11-16/0945r2.

[12] "TGax Simulation Scenarios," IEEE 802.11ax , IEEE 802.11-14/0980r1.

[13] "IEEE P802.11-Task Group AH Proposed tgah draft amendment," IEEE 802.11ah , IEEE 802.11-13/0500r1.

[14] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," in *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking*, 2003, pp. 134–146.

[15] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki - a lightweight and flexible operating system for tiny networked sensors," in *29th Annual IEEE International Conference on Local Computer Networks*, Nov 2004, pp. 455–462.

[16] M. Lacage and T. R. Henderson, "Yet another network simulator," in *Proceeding from the 2006 Workshop on Ns-2: The IP Network Simulator*, 2006.