Enhancement of the TXOP Sharing designed for DL-MU-MIMO IEEE 802.11ac WLANs

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***Abstract*—IEEE 802.11ac is one of the ongoing Wireless Local Area Network (WLAN) standard aiming to support Very High Throughput (VHT) with data rate up to 7 Gbps below the 6 GHz band. This new generation of 802.11 WLANs is expected to support Down-Link Multi-User Multiple-Input Multiple-Output (DL-MU-MIMO) transmission, which is a promising technique to greatly increase the spectral efficiency by simultaneously transmitting to multiple users. In this paper, we propose to enhance the TXOP Sharing mechanism, introduced in the 802.11ac amendment, to achieve efficient DL-MU-MIMO transmission. At first, we give new definitions about both events of successful and failed DL-MU-MIMO transmission. Then, we devise a revised Backoff procedure for the primary Access Category (AC) in order to improve the DL-MU-MIMO. Simulation results demonstrate the benefits of the enhanced TXOP Sharing Mechanism in terms of channel utilization and achieved throughput.**

I. Introduction

The last decade has witnessed a massive deployment of WLAN in several contexts (home, public hotspot, entreprise, etc.), putting WLAN in the top of the most used wireless technology. Such popularity is due to several factors, and particularly, to the emergence of new standards that aim to improve quality of service (802.11e) and to achieve very high throughput (802.11n, 802.11ac, 802.11ad, etc.). Among the new emerged 802.11 standards, the IEEE 802.11ac has been published in order to provide at least 500 Mbps of single-station throughput and more than 1 Gbps of multi-station throughput [1]. Some key features to increase data throughput are wider channel bandwidth up to 160 MHz, higher order coding rate 256 Quadrature Amplitude Modulation (256 QAM), and support for multiple (up to 8) spatial streams using Multiple-Input Multiple-Output (MIMO) techniques [2]. But the most important Physical (PHY) layer improvement of the IEEE 802.11ac, compared to its predecessor standard (IEEE 802.11n), is its Down-Link Multi-User MIMO (DL-MU-MIMO) transmission [3].

MIMO is one form of the smart antenna technology that uses multiple antennas at both the sender and the receiver to improve communication performance. A MIMO system takes advantage of two types of gains, namely: spatial diversity gain and spatial multiplexing gain. Spatial diversity could combat severe fading and improve the reliability of the wireless link by duplicating information across multiple antennas. Spatial multiplexing takes advantage of the multiple physical paths between the sender and receiver's antennas to carry multiple data streams. A Multi-User (MU) MIMO system has the potential to combine the high capacity achievable with MIMO processing with the benefits of multi-user Space Division Multiple Access (SDMA) [4]. The form of MU-MIMO adopted in 802.11ac standard is Down-Link (DL) MU-MIMO, which allows a sender station to simultaneously transmit multiple data streams for multiple receiver stations by taking advantage of a multiplexing gain through spatial division multiplexing. In this scheme, independent data streams for multiple users are multiplexed in a single Physical Layer Convergence Procedure (PLCP) Protocol Data Unit (PPDU) [5].

The Enhanced Distributed Channel Access (EDCA) function is the most commonly implemented medium access method in today's WLAN products. With the adoption of the DL-MU-MIMO transmission in the 802.11ac amendment, the EDCA function has been modified accordingly to enable, at the MAC layer level, multiple and simultaneous data streams from a sender station to multiple receiver stations. It is worth noting that the original MAC layer of 802.11 standard was designed to only support one-in-one communications. Therefore, some modifications have been introduced to the EDCA function, in order to support the DL-MU-MIMO transmission. Among these modifications, the TXOP Sharing mechanism is considered as the most important change of the basic EDCA function of the current 802.11 standard [6].

In this paper, we propose an enhanced version of the TXOP Sharing mechanism in order to improve the utilisation of the DL-MU-MIMO transmission. To achieve this objective, we propose a modification to the current 802.11ac amendment to allow the primary AC (which manages the DL-MU-MIMO transmission) to recognize the reason of failure transmission of its frames. Based on this modification, we give new definitions about the events of successful and failed DL-MU-MIMO transmission, and accordingly we propose a modified backoff procedure for the primary AC.

The remainder of this paper is structured as follows: the TXOP Sharing and the proposed solutions enhancing its performance are presented in section II. In section III, we describe our solution to enhance the TXOP Sharing. Simulation results are presented in section IV to show the effectiveness of the proposed solution. Section V concludes the paper.

II. Related Work

A. Background

The TXOP mechanism has been proposed by the 802.11e task group, and it was introduced in the IEEE 802.11 standard in 2005. The principle of the TXOP mechanism consists

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on providing Quality of Service (QoS) to WLANs. The TXOP mechanism extends the original Distributed Coordination Function (DCF) of MAC layer by allowing a specific AC, once it wins the channel access, to transmit during a bounded period as many frames as possible, as long as the limit of its TXOP is not exceeded. Note that only AC[VO] (Voice) and AC[VI] (Video) are allowed to transmit multiple frames, while AC[BK] (Background) and AC[BE] (Best Effort) are limited to transmit only one frame. The TXOP mechanism has become one of the fundamental QoS mechanisms of WLAN, and it has been implemented in all manufactured WiFi products [6].

However, some of the existing TXOP rules become obsolete and invalid with the adoption of the DL-MU-MIMO transmission in 802.11ac. Indeed, these rules assume one-in-one transmission allowing only one AC to win the internal competition and transmit during the won TXOP. So, the existing TXOP rules are not conform with the DL-MU-MIMO transmission, where the aim is to transmit multiple data streams from one sender station to multiple receiver stations. To support the DL-MU-MIMO transmission, the 802.11ac amendment has adopted the TXOP Sharing mechanism.

Usually, an EDCA TXOP has two modes in the current 802.11 standard, the initiation of the TXOP and the multiple frame transmission within a TXOP. These two modes occur respectively, when the EDCA rules permit access to the medium, and when an EDCA Function (EDCAF) retains the right to access the medium. In 802.11ac, the initiation mode is kept the same as in the current standard, whereas the multiple frame transmission mode was enhanced to allow the transmission of multiple and simultaneous data streams. In this context, a new mode is added to the EDCA TXOP which is the sharing of the TXOP. It occurs after the initiation mode and before the multiple frame transmission mode. In the share mode, frames may be transmitted from a secondary AC queue if the primary AC shares its TXOP, even if the backoff time counter for that secondary AC does not reach zero [7].

The main operating rules of the TXOP Sharing are given as follows: each EDCAF of a sender station competes for TXOP using its own EDCA parameters as it does in the current standard. Once an EDCAF wins a TXOP, it becomes the owner of that TXOP and its corresponding AC becomes the primary AC, while other ACs become secondary ACs. The primary AC can then decide whether to share its TXOP with the secondary ACs for simultaneous transmissions. If it does, the won TXOP becomes a Multi-User TXOP (MU-TXOP). The primary AC also can decide which secondary AC(s) to share with it the won TXOP, and which destinations to target for transmissions. In addition, the duration of the TXOP is determined by the TXOP limit of the primary AC, and the transmission time is determined by the amount of data scheduled to be transmitted by the primary AC. Once the primary AC has finished its transmission, the MU-TXOP is ended, even if the secondary ACs still have frames to send [8].

In figure 1, we illustrate how different ACs are able to share an EDCA TXOP for simultaneous transmissions of multiple frames. In this figure, we assume that AC[VI] is the primary AC (i.e., the AC that won the internal competition). We also assume that this AC has two blocks of MAC Protocol Data Unit (MPDU) frames, called also Aggregated MPDU (A-MPDU) frames. The first A-MPDU has for destination the station “1” (S1), and the second A-MPDU is intended for the station “3” (S3). So, both S1 and S3 are also called primary destinations. AC[VO] and AC[BE] are secondary ACs, and station “2” is secondary destination. We show in this figure that, among the secondary ACs, higher priority traffic gets the right earlier to transmit during the MU-TXOP. For example, the AC[VO] has transmitted earlier than AC[BE].

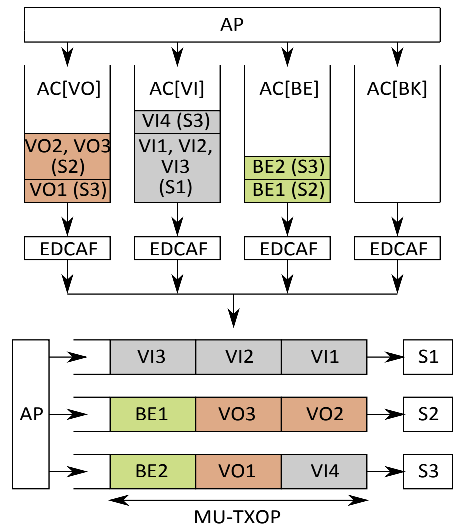


Fig. 1. An example illustrating the TXOP Sharing mechanism.

B. Existing solutions

In this section, we present existing works that aimed to enhance the TXOP Sharing mechanism since the publication of its first version in 2011 until the apparition of its latest version in 2013.

In 2011, *Zhu et al.* [9] were the first authors in the literature who addressed the EDCA function anomaly when enabling the DL-MU-MIMO transmission at the MAC layer level. In the same paper [9], *Zhu et al.* have proposed the basic idea of the TXOP sharing mechanism, which allows different ACs to transmit multiple and simultaneous data streams to multiple receiver stations. However, details about operating rules of the TXOP Sharing mechanism were not given in [9]. Especially, the needed details are a clear definition about the events of successful and failed DL-MU-MIMO transmission, and accordingly on the behavior of the primary AC and the secondary ACs concerning the backoff procedure.

In 2012, the 802.11ac task group accepted the modifications proposed for the EDCA function, which allow enabling DL-MU-MIMO transmission at the MAC layer level. Thus, the TXOP Sharing mechanism has been included in the 802.11ac amendement since the publication of its draft 1.0 [8].

The main operating rules of the TXOP Sharing mechanism, as described in 802.11ac draft 1.0 and illustrated in figure 2, are:

1) A DL-MU-MIMO transmission is successful, if all the ACs (primary AC and secondary ACs), which have transmitted A-MPDU frames, have received their BAs (Block-ACK);

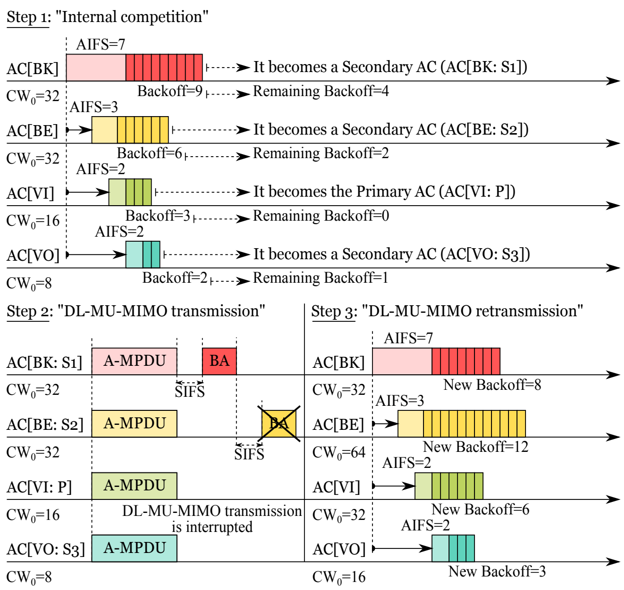


Fig. 2. The first version of the TXOP Sharing mechanism.

2) A DL-MU-MIMO transmission is failed, if at least one AC (either primary or secondary), does not receive its BA;
3) The backoff procedure of the primary AC and the other secondary ACs remains the same, as it was defined in the original EDCA function.

The above operating rules of the TXOP Sharing mechanism have been severely criticized by *Zhu et al.* in 2012 [10]. The most contraints of these rules are:

1) A secondary AC which has obtained the right to transmit during the primary AC TXOP, should not be deprived of its own chance to get a TXOP (see step 3 of figure 2);
2) When a BA of a given AC is not received, the primary AC is penalized, even if the lost of this BA concerns a secondary AC (see step 2 of figure 2)

So, in order to preserve the chances of secondary ACs to get their TXOPs, *Zhu et al.* proposed in [10] that the Contention Windows (CW) size and the backoff time counters of secondary ACs should not be changed after the DL-MU-MIMO transmission, whatever the transmission status of their frames (success or failure). Figure 3 illustrates the proposed solution, where we remark that all secondary ACs preserve the size of their contention windows and the remaining time of their backoff counters, except for the primary AC which increases its CW and chooses a new backoff time counter.

Otherwise, *Zhu et al.* in 2013 [11] proposed that, when a given secondary AC does not receive its BA, the DL-MU-MIMO transmission should not be interrupted only if the primary AC does not receive its BA, because the primary AC is the owner of the won TXOP (see step 2 of figure 4).

Another enhancement of the TXOP Sharing mechanism proposed by *Zhu et al.* [11] concerns the case where the primary AC does not receive its BA. Indeed, this situation does not mean that the other secondary ACs also fail to receive their

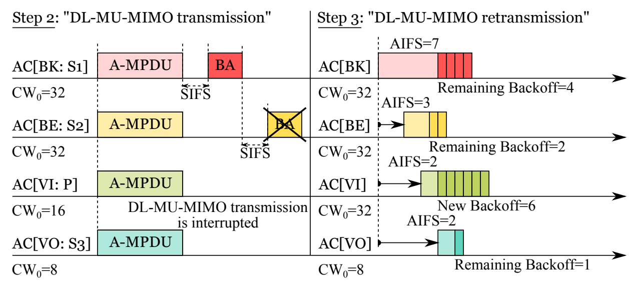


Fig. 3. The second version of the TXOP Sharing mechanism.

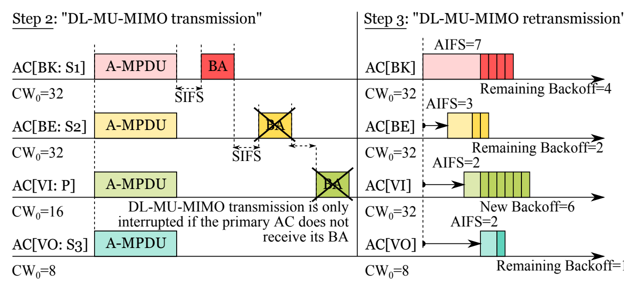


Fig. 4. The third version of the TXOP Sharing mechanism.

BAs. So, before the primary AC interrupts the DL-MU-MIMO transmission, it should first wait that the other secondary ACs receive their expected BAs (see figure 5).

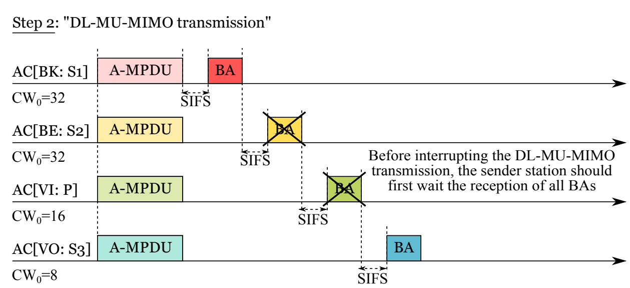


Fig. 5. The fourth version of the TXOP Sharing mechanism.

All the solutions proposed by *Zhu et al.* [10] and [11] in order to enhance the TXOP Sharing mechanism have been approved by the 802.11ac task group, and then included in the 802.11ac amendment draft 7.0 [1].

III. Proposed Solution

In this section, we propose an enhancement of the latest version of the TXOP sharing mechanism published in the 802.11ac amendment draft 7.0 [1]. The key objective of the proposed solution is to improve the DL-MU-MIMO transmission in order to better use the wireless bandwidth and hence increase the overall throughput.

Although the TXOP Sharing mechanism has been proved efficient by *Yazid et al.* [12] (through mathematical modeling and analysis) to improve the utilization of the scarce wireless bandwidth while achieving channel access fairness among the different ACs, according to *Gong et al.* [13] the TXOP Sharing mechanism could be further enhanced in order to better utilize the DL-MU-MIMO transmission.

Indeed, *Gong et al.* [13] have shown that, when multiple and simultaneous data streams are transmitted from a sender station to multiple receiver stations, if at least one of the receiver stations indicates the correct reception of some new MPDUs, the sender station can assume that there is no collision. Otherwise, if no receiver station has indicated correctly received new MPDUs, then the sender station assumes a collision.

With the actual version of the TXOP Sharing mechanism, at each time the primary AC does not receive its BA, regardless if the other secondary ACs have received or not their BAs, it assumes that the reason of loss of its A-MPDU is due to a collision. So, the primary AC stops the DL-MU-MIMO transmission, and it increases the size of its contention window before trying to win a new TXOP. Consequently, the bandwidth is less used, which decreases the amount of data successfully transmitted (i.e., the decrease of the overall throughput).

If we look in depth to the existing rules of the TXOP Sharing mechanism, we will remark two contradictory behaviors of the primary AC regarding the loss of its A-MPDU and the loss of A-MPDUs of the other secondary ACs:

- In case of one or more secondary ACs do not receive their BAs and the primary AC receives its BA, the primary AC assumes that there is no collision and the DL-MU-MIMO transmission is only ended when the limit of the won TXOP is reached.
- Contrariwise, in case of one or more secondary ACs receive their BAs and the primary ACs does not receive its BA, the primary AC assumes a collision and the DL-MU-MIMO transmission is ended even if the limit of the won TXOP is not reached.

In our proposal, we rely on the idea given by *Gong et al.* in order to enhance the TXOP Sharing mechanism. In the following, we describe the proposed improvements:

- We first introduce the idea of *Gong et al.* in order to allow the primary AC to differentiate between the reasons of failure transmission (collision or errors transmission);
- Then, we give new definitions about the events of successful and failed DL-MU-MIMO transmission, and accordingly we propose a revised Backoff procedure for the primary AC.

The key modification we introduce to the current version of the TXOP Sharing mechanism, is as follows: when the primary AC does not receive its BA and at least one of the other secondary ACs receive its BA, the primary AC assumes that its A-MPDU frame is not lost because of collision but to another reason, which can be noise errors for example. In other words, the primary AC assumes a collision only in one case: when it does not receive its BA and none of the secondary ACs receives its BA.

According to the modification presented above, we are able to give new definitions about both events of successful and failed DL-MU-MIMO transmission, as follows:

- A DL-MU-MIMO transmission is successful, if at least one AC (either primary or secondary) has received its BA;
- A DL-MU-MIMO transmission is failed, if none of the ACs (primary and secondary) has received its BA.

Based on the new definitions of successful and failed DL-MU-MIMO transmission, the behavior of the primary AC is modified as follows:

When the primary AC does not receive its BA, and at least one of the other secondary ACs receives its BA, the primary AC concludes that there is no collision. Thus, instead of interrupting the DL-MU-MIMO transmission and doubling its contention window, we propose that the primary AC and the other secondary ACs continue to transmit until the limit of the TXOP is reached. However, if the primary AC detects no collision and the TXOP duration is expired, the primary AC liberates the channel and attempts to win the channel again, but after having initialized its contention window at the minimal size. Otherwise, if the primary AC does not receive its BA, and none of the secondary ACs receives its BA, the primary AC concludes that a collision occurred on the channel. Therefore, it liberates the channel and it follows the exiting rules of the TXOP Sharing mechanism.

In figure 6, we illustrate the main rules of the enhanced version of TXOP Sharing mechanism. On the one hand, we show in step "2" that the AC[VI] (which is the primary AC) persists in DL-MU-MIMO transmission although it has not received its BA, because there are two secondary ACs (AC[BK] and AC[VO]), which have received their BAs. On the other hand, we show in step "3" that when the primary AC does not receive its BA and the limit of the won TXOP is reached, the primary AC interrupts the DL-MU-MIMO transmission although there are two secondary ACs, which have received their BAs. However, before the primary attempts again to win a new TXOP, it first initialized its contention window at its minimal value.

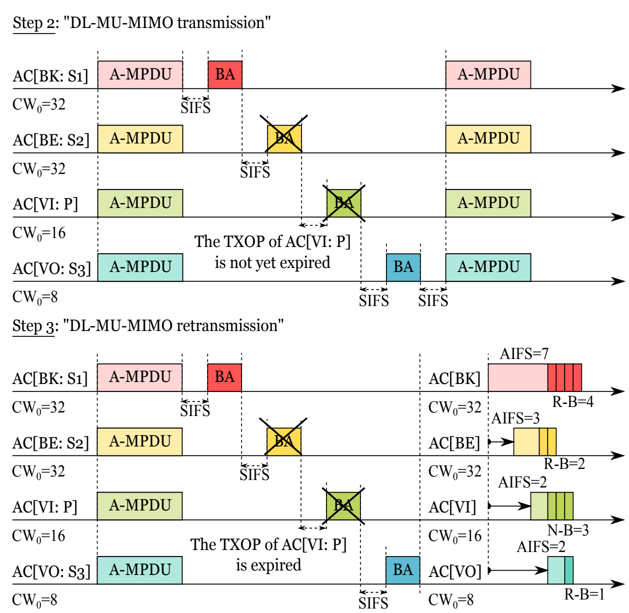


Fig. 6. The enhanced version of the TXOP Sharing mechanism.

IV. Simulation Results

In this section, we present the simulation results obtained with both enhanced and standard versions of the TXOP Sharing mechanism. Here, we particularly focus on the overall throughput metric. The simulations have been done in a custom-made simulator, which is an event-driven simulation program written in C++ programming language under Linux operating system. The main motivations for implementing the TXOP Sharing mechanism in a custom-made C++ simulator rather than in any other well known simulators (such as ns-2), are the possibility of isolating the IEEE 802.11ac performance from the rest of the network and the faster execution of the simulations. The 802.11ac PHY and MAC parameters used in the simulations are listed in table I.

TABLE I. 802.11AC PHY AND MAC PARAMETERS.

PHY Parameters	***Numerical values***
Time Slot (TS)	9 μs
SIFS	16 μs
Minimum data rate	58,5 Mbps
Maximum data rate	780 Mbps
Minimum PHY header time	40 μs
Maximum PHY header time	68 μs
Propagation delay	1 μs
MAC Parameters	***Numerical values***
Maximum MAC header length	36 bytes
Maximum MPDU length	11454 bytes
Maximum Block-ACK length	40 bytes
Maximum Backoff stage [BK, BE, VI, VO]	[5, 5, 1, 1]
AIFS [BK, BE, VI, VO]	[7, 3, 2, 2]$\times$TS+SIFS
CW_0 [BK, BE, VI, VO]	[32, 32, 16, 8]
TXOPLimit [BK, BE, VI, VO]	[0, 0, 6016, 3264]μs

Since the goal of the enhanced version of the TXOP Sharing mechanism is to achieve better utilization of the DL-MU-MIMO transmission when noise errors happen on the transmitted A-MPDU frames (in addition to collisions related losses), in all simulation scenarios we are interested to a small network size. Regarding the TXOPLimit of different ACs, we have only mentioned (in the figures) the TXOPLimit[VI] since the TXOPLimits were fixed as follows: TXOPLimit[VO]=TXOPLimit[VI]/2, and TXOPLimit[BE]=TXOPLimit[BK]=1.

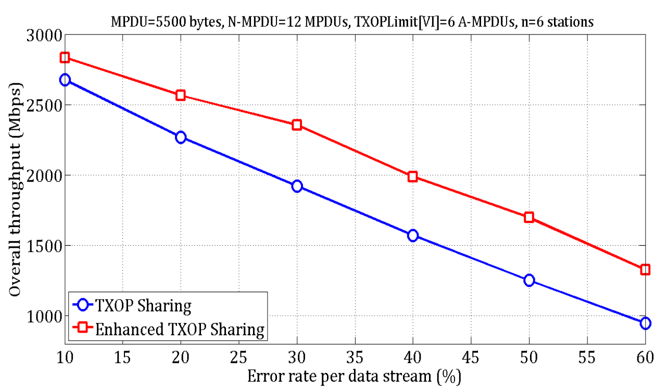


Fig. 7. Throughput vs. error rate per data stream.

In figure 7, we compare the overall throughputs obtained with the enhanced version and the standard version of the TXOP Sharing mechanism according to the error rate per data stream. We see that the achieved throughput is inversely propositional to the per stream error rate in both mechanisms. Further, the throughput obtained with the enhanced TXOP Sharing is considerably higher than the one of the classical TXOP Sharing. We argue this by the fact that at each time the primary AC does not receive its BA and at least one of the other secondary ACs receives its BA, the primary AC and the other secondary ACs continue to transmit their A-MPDU frames until the limit of the won TXOP is reached.

In figure 8, we compare the achieved throughput of both enhanced and classical versions of the TXOP Sharing mechanism by report to the limit of the won TXOP. We clearly remark the ability of the proposed TXOP Sharing mechanism to reach higher throughputs in 802.11ac WLAN. Moreover, we observe that the achievable throughput is proportional to the limit of the won TXOP. This is due to fact that the DL-MU-MIMO transmission is only interrupted if the primary AC has not received its BA and none of the other secondary ACs has received its BA.

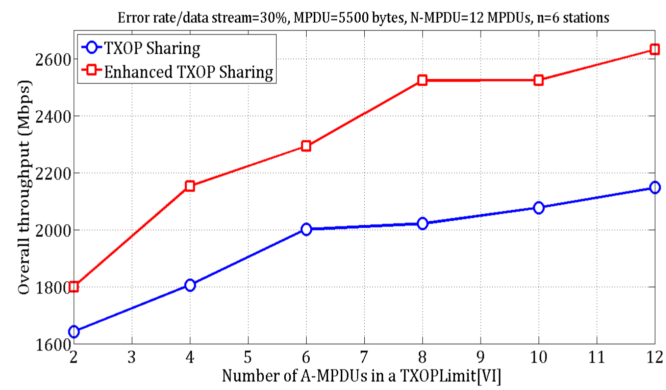


Fig. 8. Throughput vs. TXOPLimit.

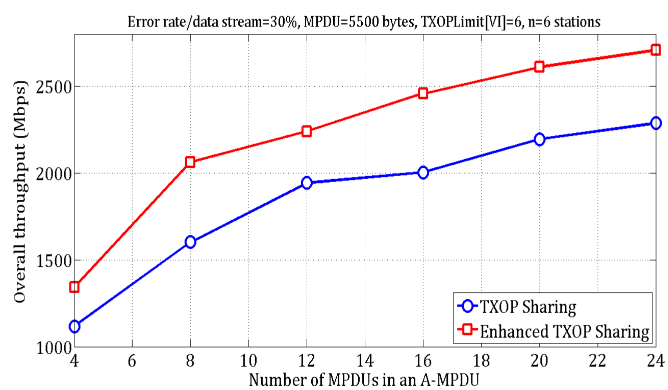
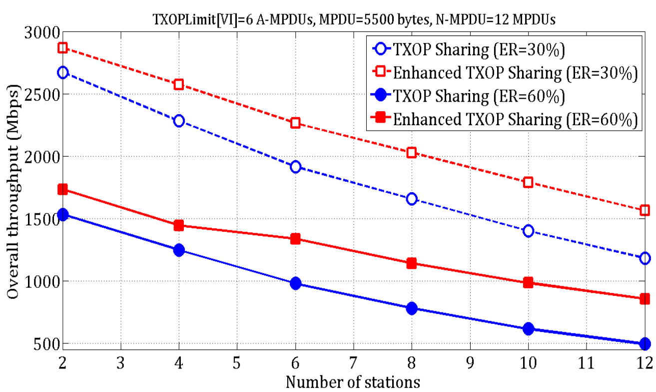


Fig. 9. Throughput vs. A-MPDU length.

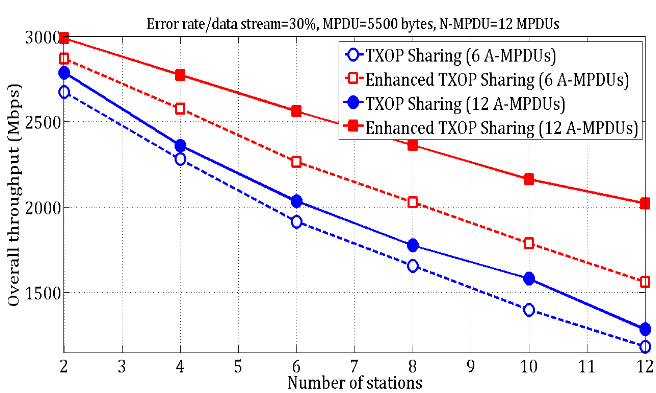
Since the A-MPDU length has a significant impact on increasing the throughput in 802.11ac WLAN, in figure 9 we have fixed the MPDU length at its middle value (5500 bytes) and we have varied the number of MPDUs within A-MPDU frame. This allows us to compare the achievable throughputs between the enhanced version and the classical TXOP Sharing mechanism. We remark on this figure that, the achievable throughput increases with the increase of the A-MPDU length (i.e., the number of MPDUs within A-MPDU frame). The enhanced TXOP Sharing mechanism gives better overall throughput, because the DL-MU-MIMO transmission is only interrupted if none of the ACs (either primary or secondary) has received its BA. Thus, the amount of transmitted data is increased.

In figures 10(a), we have chosen two values of per data stream error rate (30% and 60%), in order to compare the obtained throughputs between the enhanced and the standard versions of the TXOP Sharing mechanism according to number of stations in the network. We remark that the enhanced TXOP Sharing mechanism allows to increase significantly the overall throughput, even when the per data stream error rate is very high. We justify this behavior by the fact that in the existing TXOP Sharing, the DL-MU-MIMO transmission is interrupted each time the primary AC does not receive its BA. However, with the enhanced TXOP Sharing mechanism, the DL-MU-MIMO transmission is interrupted only if none of the ACs (primary or secondary) has received its BA.

In Figure 10(b), we have chosen two limits of the won TXOP (6 and 12 A-MPDUs), in order to clearly see the ability of the proposed TXOP mechanism to enhance the bandwidth utilisation and hence increase the overall throughput. We observe that increasing the limit of the won TXOP allows to improve significantly the overall throughput obtained with the enhanced version of the TXOP Sharing. Although noise errors can happen on the data streams transmitted by the primary AC, if at least one of the other secondary ACs receives its BA, the primary AC does not interrupt the DL-MU-MIMO transmission.



(a)



(b)

Fig. 10. Throughput vs. number of stations in the network.

V. Conclusion

In this paper, we have proposed an enhancement of the TXOP Sharing mechanism in order to efficiently utilize the DL-MU-MIMO transmission. Within the envisioned enhancement of the TXOP Sharing mechanism, the DL-MU-MIMO transmission is interrupted only if the primary AC does not receive its BA and also none of the secondary ACs receives its BA. Simulation results clearly demonstrate the superiority of the proposed solution by report to the classical TXOP Sharing mechanism. As an extension of this work, we propose to prove the efficiency of the enhanced TXOP Sharing mechanism by means mathematical modeling and analysis.

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