Performance Analysis of the TXOP Sharing Mechanism in the VHT IEEE 802.11ac WLANs

Mohand Yazid, Adlen Ksentini, Louiza Bouallouche-Medjkoune, and Djamil Aïssani

Abstract—The 802.11ac amendment of the IEEE 802.11 standard, known as a very high-throughput wireless local area network (WLAN), has attracted extensive attention for achieving a maximum transmission rate up to 7 Gb/s. This is mainly possible by adopting the DownLink Multiple-User Multiple-Input—Multiple-Output (DL MU-MIMO) technology, which allows multiple frames to be simultaneously transmitted from the access point (AP) to different receivers via multiple spatial streams. To support the DL MU-MIMO technology at medium access control level, a technique called transmission opportunity (TXOP) sharing has been proposed to extend the mandatory TXOP of the WLAN standard. In this letter, we propose an analytical model based on Markov chains to evaluate the performance of an IEEE 802.11ac AP enabling the TXOP sharing mechanism. Based on this model, we are able to derive the achievable throughput of a given access category (AC), namely, voice (VO), video (VI), best effort (BE), and background (BK). The ultimate goal of this letter is to analyze how the TXOP sharing mechanism could improve the utilization of the scarce wireless bandwidth while achieving channel access fairness among the different ACs. Note that the obtained theoretical results are also validated by computer simulation.

Index Terms—VHT IEEE 802.11ac WLANs, TXOP sharing mechanism, modeling, Markov chains, throughput analysis, model validation.

I. INTRODUCTION

The IEEE 802.11ac Task Group (TGac) is actively working on an amendment that permits to reach a maximum aggregate throughput up to 7 Gb/s on bands below 6 GHz in WLAN. In particular, the Medium Access Control (MAC) throughput envisioned by the 802.11ac amendment is at least 500 Mbps for Single-User (SU), and at least 1 Gb/s for Multi-User (MU) [1]. Due to the significant increase of transmission rate that could be achieved by the 802.11ac amendment, the term Very High Throughput (VHT) is also associated to this new amendment [2].

Multi-User Multiple-Input Multiple-Output (MU-MIMO) technology is the key feature that allows the 802.11ac reaching the gigabit transmission rate. Indeed, MU-MIMO is defined as a technique where multiple stations, each with potentially multiple antennas, can simultaneously transmit several data streams to multiple users at the same time over the same frequency channel [3].

To enable DL MU-MIMO transmission at the MAC layer level, the Transmission Opportunity (TXOP) Sharing principle has been firstly proposed by Zhu et al., in 2011 [4]. Then, the TXOP Sharing mechanism was included in the IEEE 802.11ac specifications since the draft 1.0 published in 2012 [5]. The TXOP Sharing mechanism extends the existing TXOP mechanism to simultaneously support down-link multiple data streams to multiple receivers. In fact, the TXOP mechanism was introduced in the IEEE 802.11 standard by the 802.11e Task Group (TGe) in 2005. The main goal of this mechanism was to provide Quality of Service (QoS) to the WLAN networks. In this context a new mechanism, namely Enhanced Distributed Channel Access (EDCA) TXOP, was proposed. It allows a specific Access Category (AC) to transmit a Contention Free Burst (CFB) during a bounded period. Thereby, an AC can transmit as many frames as possible, as the limit of its TXOP is not exceeded. However, some of the existing TXOP rules become obsolete and invalid with the adoption of DL MU-MIMO in 802.11ac. Indeed, these rules assume one-on-one transmission allowing only one AC to win the internal competition and transmit during the won TXOP, which is not conform to the DL MU-MIMO aim (multiple to multiple transmissions) [4]. To support the DL MU-MIMO transmission, the 802.11ac amendment has adopted the TXOP Sharing mechanism [1].

Usually, an EDCA TXOP has two modes in the current 802.11 standard, the initiation of the TXOP (which occurs when the EDCA rules permit access to the medium) and the multiple frame transmission within a TXOP (which occurs when an EDCA Function (EDCAF) retains the right to access the medium). Whereas in the 802.11ac amendment, the initiation mode is kept the same as in the current standard, while the multiple frame transmission mode was enhanced to allow multiple and simultaneous frame exchange sequences. 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 counter for that secondary AC is not at zero [6].

The main operating rules of the TXOP Sharing mechanism are: each EDCF of an AP competes for TXOP using its own EDCA parameters as it does in the current standard. Once an EDCF 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 [7].

In this letter, we propose a Markov chain-based analytical model for the TXOP sharing mechanism enabled at the 802.11ac AP. We recall that TXOP sharing mechanism represents the unique MAC feature of the IEEE 802.11ac amendment, allowing the DL MU-MIMO transmission to be achieved at the Physical (PHY) layer level. Based on the proposed Markov chain output (transmission probability of a given AC), we derive a mathematical model to estimate the achievable throughput of each AC, and hence highlight the improvement obtained in terms of bandwidth utilization and channel access fairness among the different ACs. Further, the accuracy of the proposed analytical model and the obtained numerical results are validated by computer simulation.

This letter is organized as follows: we describe the proposed analytical model for an IEEE 802.11ac AP enabling the EDCA TXOP Sharing in Section II. Then, the impact of TXOP Sharing on the achievable throughput is analyzed in Section III. Section IV concludes this letter.

II. MODELING OF IEEE 802.11AC WITH TXOP SHARING

In this section, we propose a 2-D discrete time Markov chain, which models an IEEE 802.11ac AP enabling the TXOP Sharing mechanism in order to estimate the transmission probability \( \tau[h] \) for each of its AC[\( h \)] (where \( h \in \{ VO, VI, BE, BK \} \)). Then, using the computed \( \tau[h] \), we analyze the different events that can occur within the channel transmission aiming at developing a mathematical model to derive the achievable throughput \( TH[h] \) of each AC[\( h \)].

A. Assumptions and Parameters of 802.11ac Analytical Model

Before detailing the proposed analytical model, we begin by presenting a list of considered assumptions in this work. The list of parameters is provided in Table I. Note that \( P_0[h] \) is the probability to find the channel busy for an AC[\( h \)], and \( P_{sh} \) is the probability to share a TXOP between the ACs.

1) The transmission queue of each AC[\( h \)] is assumed to be always non-empty (saturation conditions) in order to reach the maximum achievable throughput of an AC[\( h \)].

2) The collision probability \( P_c[h] \) of an AC[\( h \)] is constant and independent from the number of retransmissions. It is the key approximation in Bianchi’s model [8] which verifies the Markov property in the proposed chain.

Once the key approximation in Bianchi’s model [8] is assumed, it is possible to model the bi-dimensional process \( \{ S[h](t), B[h](t) \} \) with the Markov chain depicted in Fig. 1. An AC[\( h \)] can be either in backoff states \( (i,k) \), or in transmission states \( (i,-k) \). With the probability \( 1 - P_0[h] \), the AC[\( h \)]

<p>| Table 1 Parameters of 802.11ac Analytical Model |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>( m[h] )</td>
<td>Maximum backoff stage of the AC[( h )].</td>
</tr>
<tr>
<td>( W_0[h] )</td>
<td>Minimum contention window of the AC[( h )].</td>
</tr>
<tr>
<td>( W_m[h] )</td>
<td>Maximum contention window of the AC[( h )].</td>
</tr>
<tr>
<td>( T_I[h] )</td>
<td>Contention window size at backoff stage ( i ).</td>
</tr>
<tr>
<td>( AMPDU )</td>
<td>Number of AMPDUs of the AC[( h )] in its TXOP[h].</td>
</tr>
<tr>
<td>( T_{AMPDU} )</td>
<td>AMPDU length.</td>
</tr>
<tr>
<td>( TP{PHY} )</td>
<td>Transmission time of an AMPDU.</td>
</tr>
<tr>
<td>( T_BA )</td>
<td>Time duration of the PHY header.</td>
</tr>
<tr>
<td>( AIFS )</td>
<td>Transmission time of a Block Acknowledgment.</td>
</tr>
<tr>
<td>( SIFS )</td>
<td>Time of an arbitration inter-frame space.</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Time of a short inter-frame space.</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>An empty slot time.</td>
</tr>
</tbody>
</table>
decrements its backoff counter, with the probability \( P_b[h](1 - P_{sh}) \), the AC\([h]\) freezes its backoff timer, and with the probability \( P_b[h]P_{sh} \), the AC\([h]\) enters immediately to transmission states meaning that the channel is shared. Otherwise, the AC\([h]\) must decrement its last backoff timer before accessing to the transmission states. Finally, with the probability \((1 - P_c[h])\), the first AMPDU is successfully transmitted and the channel is reserved for the other AMPDUs.

Let \( \pi_{i,k} = \lim_{n \rightarrow \infty} P\{S[h](t) = i, B[h](t) = k\} \) be the stationary distribution of the chain. The closed-form solution for this Markov chain is

\[
\pi_{i,k} = \begin{cases} 
\frac{(P_c[h])^i \cdot \alpha}{\sum_{i=0}^{m[h]} \cdot \sum_{k=0}^{P_{sh}[n]}}, & i \in (0, m[h] - 1), k = 0; \\
\frac{P_b[h] \cdot \alpha}{\sum_{i=0}^{m[h]} \cdot \sum_{k=0}^{P_{sh}[n]}}, & i \in (0, m[h] - 1), k \in (1, W_i[h] - 1); \\
\frac{\gamma \cdot \pi_{0,0}}{\sum_{i=0}^{m[h]} \cdot \sum_{k=0}^{P_{sh}[n]}}, & i \in (0, m[h]), k \in (-1, -TL[h] + 1) 
\end{cases}
\]

where

\[
\alpha = \frac{P_c[h]^i}{\sum_{i=0}^{m[h]} W_i[h] \cdot P_b[h] \cdot P_{sh}}, \quad \gamma = (1 - P_c[h]) \cdot P_c[h]^i.
\]

Thus, by the relation (3), all the values \( \pi_{i,k} \) are expressed as a function of the value \( \pi_{0,0} \). \( \pi_{0,0} \) can be obtained by imposing the normalization condition as follows:

\[
1 = \sum_{i=0}^{m[h]} W_i[h] \cdot P_b[h] \cdot P_{sh} + \sum_{i=0}^{m[h]} P_b[h] \cdot P_{sh} \cdot (1 - P_c[h]) \cdot TL[h] - 1
\]

\[
= \left[ (1 - P_c[h]) \cdot P_b[h] \cdot P_{sh} + (1 - P_c[h]) \cdot TL[h] - 1 \right] \cdot \pi_{0,0}.
\]

Hence, we have

\[
\pi_{0,0} = \frac{(1 - P_c[h]) \cdot P_b[h] \cdot P_{sh}}{P_b[h] \cdot P_{sh} + (1 - P_c[h]) \cdot TL[h] - 1}.
\]

The probability \( P_b[h] \) that a transmitted AMPDU of an AC\([h]\) encounters a collision when at least one of higher priority AC\([i]\) (\( i > h \)) transmits, is given as follows:

\[
P_b[h] = 1 - \prod_{i > h} (1 - \tau[i]).
\]

Now, the transmission probability \( \tau[h] \) can be computed as the sum of all steady probabilities of transmission states. Thus

\[
\tau[h] = \sum_{i=0}^{m[h]} \sum_{k=0}^{m[h]} \pi_{i,k} + \sum_{i=0}^{m[h]} \pi_{i,0},
\]

\[
= TL[h] \cdot (1 - P_c[h]) + P_c[h] \cdot \frac{1}{1 - P_c[h]} \cdot \pi_{0,0}.
\]

The probability to share a TXOP is given as follows:

\[
P_{sh} = 1 - \frac{A_w}{A_t}.
\]

Where \( A_w \) and \( A_t \) are respectively the number of antennas used by the primary AC and the maximum number of antennas available at the AP. In reality the number of antennas \( (A_w) \) is station-dependant, but for simplicity we assume that all ACs use the same value of \( A_w \).

Equations (9), (10) and (11) form a set of nonlinear equations, which can be solved by means of numerical methods.

C. Saturation Throughput (\( TH[h] \))

Based on the obtained \( \tau[h] \), we compute the achievable throughput \( TH[h] \) of an AC\([h]\) as follows:

- Let \( P_s[h] \) be the probability that there is exactly one AC\([h]\) transmitting on the channel:

\[
P_s[h] = \tau[h] \cdot \prod_{i \neq h} (1 - \tau[i]).
\]

- Let \( T_s[h] \) be the successful transmission time of an AC\([h]\):

\[
T_s[h] = AIFS[h] + TL[h] \cdot \left( T_{PHY} + T_{AMPDU} + 2 \cdot SIFS + 2 \delta + T_{EA} \right) - SIFS.
\]

Now, we define by \( E_s[h] \) and \( E_s[\sigma] \), respectively, the average amount of successful transmitted data and the average time
between two consecutive transmissions

\[
E_I[h] = P_s[h] \cdot AMPDU \cdot TL[h] + (1 - P_s[h]) \sum_{i \neq h} P_s[i] \cdot AMPDU \cdot TL[i] \\
\times P_{sh} \cdot \frac{1}{\sum_{i \neq h} P_s[i]}.
\]  

(15)

\[
E[\sigma] = \sum_{i \neq h} P_s[i] \cdot T_s[i] \cdot \frac{1}{\sum_{i \neq h} P_s[i]}.
\]  

(16)

The achievable throughput \(TH[h]\) of an AC\(\{h\}\) is obtained as the ratio of \(E_I[h]\) and \(E[\sigma]\)

\[
TH[h] = \frac{E_I[h]}{E[\sigma]}.
\]  

(17)

III. ANALYSIS OF IEEE 802.11AC WITH TXOP SHARING

In this section, we analyze the achieved throughput for the different ACs of an IEEE 802.11ac AP, which enables the TXOP Sharing mechanism. The obtained analytical results are validated by simulation. So, we have implemented the EDCA function with TXOP Sharing in a custom-made simulator written in C++. The main motivations are the possibility of isolating the 802.11ac MAC performance from the rest of the network and the faster execution of simulations. Table II denotes the 802.11ac PHY and MAC parameters used in both the numerical resolution and simulation.

Fig. 2(a) and (b) illustrate the throughput variation of a given AC according to the probability of sharing. We remark that, the throughput of each AC increases with the increase of the probability of sharing. By enabling the TXOP sharing mechanism, it is possible to transmit during a TXOP of another AC. This explains why there is a significant improvement of the achievable throughput of a given AC with the use of TXOP sharing mechanism. Finally, from Fig. 2(a) and (b) we observe that, when the probability of sharing is high \((P_{sh} \geq 0.7)\), the throughput of all ACs converges to the same value, because the ACs transmit all time when a given AC wins the channel. It is important to note that high values of \(P_{sh}\) indicate that the number of used antennas \((A_u)\) is high. Therefore, there is a possibility to efficiently take advantage from high spatial reuse to increase the throughput.

IV. CONCLUSION

In this letter, we presented an analytical model based on a Markov chain to analyze, for the first time in the literature, the TXOP Sharing mechanism included in the 802.11ac specifications to enable the DL MU-MIMO transmission at MAC level. Numerical results, validated by computer simulation, clearly show the benefit of using the TXOP Sharing mechanism in order to improve the utilization of the scarce wireless bandwidth and increase channel access fairness among the different ACs.

REFERENCES


