

# On Throughput Estimation with TXOP Sharing in IEEE 802.11ah Networks

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**Abstract**—Nowadays the concept of the Internet of Things (IoT) becomes more and more popular. However, state-of-the-art wireless technologies do not meet the IoT requirements for low power consumption and big number of simultaneously connected devices. To meet IoT requirements, IEEE 802.11 Working Group is developing a new low-power long-range Wi-Fi, called HaLow, which is described in the new IEEE 802.11ah amendment to the Wi-Fi standard. To increase the network coverage and decrease power consumption of sensors, the new amendment introduces relaying. A part of this mechanism is TXOP sharing, which hastens two-hop frame exchange. In this paper, we develop the first analytical model of relaying with TXOP sharing in IEEE 802.11ah networks, which allows estimating network throughput.

**Index Terms**—IEEE 802.11ah, Wi-Fi HaLow, TXOP sharing, Throughput, Relays.

## I. INTRODUCTION

Nowadays Wi-Fi [1] has become a dominant technology for wireless local area networks (WLANs). The IEEE 802.11 Working Group – which standardizes Wi-Fi – is continuously developing new amendments to improve Wi-Fi performance in emerging scenarios. In particular, IEEE 802.11ah, a novel amendment which expected to be ready in 2016, focuses on the Internet of Things (IoT) concept and its scenarios [2]. IoT will connect together billions of power-limited autonomous actuators and sensors such as water, humidity, electricity meters. 802.11ah, which is also known as Wi-Fi HaLow, will provide wireless connectivity for such a swarm of devices. To support IoT requirements, 802.11ah introduces many features [2], e.g. restricted access window mechanism, centralized authentication control, etc., which have been already studied in [3]–[6].

To increase the coverage of the 802.11ah network, the new amendment introduces relaying. So in a 802.11ah network, edge stations (STAs) can send packets to the Access Point (AP) via relays, see Fig. 1. Relaying can shorten transmission duration and reduce energy consumption. Indeed, if a relay is located closer to the STA than the AP, the STA can use a faster Modulation and Coding Scheme (MCS), thus shortening transmission, and/or transmit packets at lower power.

Despite the aforementioned advantages, the usage of relays has some drawbacks. For example, with the default Enhanced Distributed Channel Access (EDCA) [1], it is needed to perform the channel access procedure twice to transmit a packet (see Fig. 2a), which increases channel time consumption, packet delivery time, and packet collision probability. To

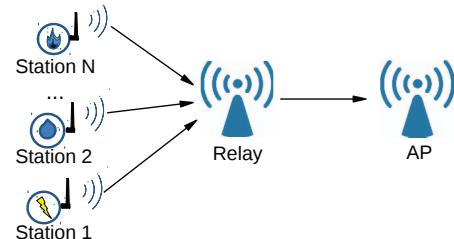


Figure 1. Considered network

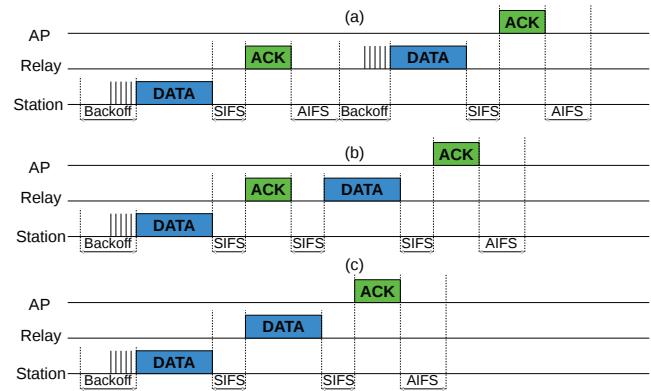


Figure 2. Single packet transmission using (a) legacy relaying, (b) TXOP sharing with explicit and (c) implicit ACK

get rid of these drawbacks, 802.11ah introduces transmission opportunity (TXOP) sharing mechanism for relays, described in Section II. Because of its novelty, the 802.11ah TXOP sharing mechanism has not been studied in literature yet. In this pioneering work, we develop an analytical model of TXOP sharing to estimate how it improves network performance.

Many papers aim at studying Wi-Fi channel access methods. In [7] Bianchi introduces one of the first models of Distributed Coordination Function (DCF) channel access method, which is a predecessor of EDCA. The main contribution of [7] is the virtual slot based approach, which significantly simplifies modelling. Many papers use the same slot based approach, modifying the model [7] for lossy channel [8], EDCA [9], etc.

Unfortunately, none of these models can be directly applied for the throughput estimation of the 802.11ah network with the TXOP sharing mechanism.

The rest of the paper is organised as follows. Section II briefly describes the channel access method and the TXOP sharing mechanisms in IEEE 802.11 networks. In Section III, we develop an analytical model. Section IV presents numerical results. Section V concludes the paper.

## II. TXOP SHARING IN IEEE 802.11 NETWORKS

### A. Legacy Channel Access Method EDCA

The main Wi-Fi channel access – EDCA – is based on the carrier sense multiple access with collision avoidance (CSMA/CA) method. With EDCA, packet transmission attempts are separated by backoff intervals. After its packet transmission, a STA initializes the backoff counter with a random number chosen uniformly from the interval  $[0, W - 1]$ , where  $W$  is the current contention window. Backoff counts down every time when the channel is idle for slot  $\sigma$ . If the channel becomes busy, the STA suspends the backoff counter and resumes it only when the channel is idle for Arbitration InterFrame Space (AIFS).

In Wi-Fi networks, a STA considers that the channel is busy, if it receives some signal, e.g. from a neighbor STA. Moreover, to protect their packets from collisions with transmissions of hidden STAs, STAs use a virtual carrier sense mechanism called Network Allocation Vector (NAV), which takes information about transmission durations from a special duration field present in each packet MAC header. In addition to NAV, the 802.11ah STAs can use a new virtual carrier sense mechanism called Response Indication Deferral (RID), which takes information from 2-bit Response Indication field in a packet PHY header. The PHY header is always transmitted using the most robust MCS, so it can be read even if the packet payload (including the MAC header) is corrupted. A STA considers the channel idle only if all three carrier sense mechanisms (physical carrier sense, NAV and RID) confirm it.

Before the first transmission attempt of a packet, the contention window  $W$  equals  $W_{min}$ . If the transmission attempt is unsuccessful, the STA waits for AIFS, chooses the number of backoff slots from the new contention window  $W_{new} = \min(2W, W_{max})$ , and starts the backoff counting. When the backoff counter of a STA reaches zero, the STA contends for the channel to obtain a TXOP. If the contention is successful, the STA becomes a TXOP owner and can send following packets without contention. Originally (in the IEEE 802.11e amendment which introduces TXOP), only the TXOP owner can transmit data packets during TXOP, but later amendments propose to share TXOP between the owner and other STAs.

### B. TXOP Sharing Mechanisms

IEEE 802.11n introduces the Reverse Direction (RD) protocol. RD allows the TXOP owner to request data from the receiver and, if the receiver has data, it transmits a packet to the TXOP owner without the backoff procedure. As shown

in [10], RD can reduce latency in case of bidirectional data transmission, which is typical for conferencing, TCP, etc.

IEEE 802.11ac introduces TXOP sharing mechanism which allows the AP to transmit multiple packets to different users simultaneously in the downlink, using different spatial streams. As shown in [11], 802.11ac TXOP sharing improves the utilization of the scarce wireless bandwidth.

In IEEE 802.11ah, the TXOP sharing mechanism allows a relay to share TXOP of the STA to forward the packet received from this STA to the AP and vice versa, if both the STA and the relay use the same frequency channel during TXOP. 802.11ah describes two versions of TXOP sharing, with explicit and implicit acknowledgement (ACK), respectively.

Fig. 2b shows the TXOP sharing with explicit ACK. SIFS after the packet reception, the relay sends an ACK to the STA and SIFS after that it transmits the packet to the AP.

With TXOP sharing with implicit ACK (see Fig. 2c), SIFS after the packet reception the relay forwards this packet to the AP without sending back an ACK. In this case, the relay informs the STA about successful packet reception implicitly. If SIFS after the packet transmission the STA hears the packet from the relay destined to the AP, the STA assumes that its own transmission was successful.

If the relay fails to transmit a packet during a shared TXOP, it carries out the next transmission attempt using the backoff procedure.

In this paper, we study how the TXOP sharing influences the network throughput.

## III. MODEL DESCRIPTION

Consider an 802.11ah network with 1 AP, 1 relay and  $N$  STAs (see Fig. 1). All the STAs and the relay are within the transmission range of each other. In this case, backoff counters of the relay and all the STAs are synchronized. All the STAs are in saturation, i.e. each STA always has a packet for transmission. All packets are of the same size  $d$ . The STAs transmit packets to the AP via the relay which is within the transmission range of all the STAs and the AP.

In our paper, we consider 2 scenarios. In Scenario A, all the STAs are within the transmission range of the AP, in Scenario B, all the STAs are outside of the transmission range of the AP.

We account that packet transmissions are unreliable due to noise or interference from outside the network. If only one STA transmits a packet, the transmission attempt is successful with probability  $q_S$ . Similarly, the probability that a collision free transmission of the relay is successful equals  $q_R$ .

In Scenario A, if two or more nodes transmit packets simultaneously, all of them fail. In Scenario B, if the relay and one or more STAs transmit their packets simultaneously, STAs fail, but the relay succeeds with probability  $q_R$ , because the AP can hear only transmissions made by the relay.

As in [7], we refer to the interval between two consecutive backoff countdowns as a *virtual slot*. In addition, we introduce the following probabilities:

- $p_e$  is the probability of empty slot, when all nodes are silent,
- $p_s^{(S)}$  is the probability of a given STA's successful slot, when the STA successfully transmits its packet to the relay (note that if TXOP sharing is used, in this slot the relay transmits, too),
- $p_s^{(R)}$  is the probability of the relay's successful slot, when the relay successfully transmits its packet to the AP after performing the backoff procedure,
- $p_c^{(S)}$  is the probability of a STA's unsuccessful transmission attempt, if the STA has chosen the given slot for transmission,
- $p_c^{(R)}$  is the probability of the relay's unsuccessful transmission attempt, if the relay has chosen the given slot for transmission.

Since in the considered scenarios, all packets are transmitted via the relay, the network throughput is equal to the throughput of the relay.

If the TXOP sharing mechanism is not used, the relay succeeds in packet delivery only in its successful slots, so the network throughput equals

$$S_{leg} = \frac{p_s^{(R)} d}{T_{slot}}, \quad (1)$$

where  $T_{slot}$  is the average virtual slot duration.

With the TXOP sharing mechanism, the relay succeeds both in its successful slots and in successful slots of STAs (with probability  $q_R$ ), so the network throughput equals

$$S_{TS} = \frac{(p_s^{(R)} + N p_s^{(S)} q_R) d}{T_{slot}}. \quad (2)$$

Firstly, let us find the average virtual slot duration  $T_{slot}$ . We suppose that a packet PHY header (and the Response Indication field) is always received successfully by all STAs. In the considered scenarios, the Response Indication field in data packets is set to the *NormalResponse* value, which means that after a packet transmission the medium is considered busy during SIFS plus ACK transmission duration. Because of this, the durations of successful and unsuccessful transmission attempts are the same.

Hence we obtain the following durations of different TXOPs according to Fig. 2, if STAs and the relay use the same MCS:

- $T_1 = T_{dat} + SIFS + T_{ACK} + AIFS$  is the legacy TXOP duration, where  $T_{dat}$  and  $T_{ACK}$  are durations of data packet and ACK transmission, respectively,
- $T_2 = 2 \cdot T_{dat} + 3 \cdot SIFS + 2 \cdot T_{ACK} + AIFS$  is the duration of shared TXOP with explicit ACK,
- $T_3 = 2 \cdot T_{dat} + 2 \cdot SIFS + T_{ACK} + AIFS$  is the duration of shared TXOP with implicit ACK.

Thus, we obtain the average virtual slot duration  $T_{slot}$  in case of:

- legacy packet transmission

$$T_{slot} = p_e \sigma + (1 - p_e) T_1,$$

where  $\sigma$  is the duration of empty slot,

- TXOP sharing with explicit ACK

$$T_{slot} = p_e \sigma + N p_s^{(S)} T_2 + (1 - p_e - N p_s^{(S)}) T_1,$$

- TXOP sharing with implicit ACK

$$T_{slot} = p_e \sigma + N p_s^{(S)} T_3 + (1 - p_e - N p_s^{(S)}) T_1.$$

After that, we find the probabilities of different types of slots. Let  $\tau_S$  ( $\tau_R$ ) be the probability that the marked STA (the relay) chooses a given slot for transmission.

A virtual slot is empty, if neither the relay nor a STA transmits a packet during this slot. Then the probability of empty slot equals

$$p_e = (1 - \tau_R)(1 - \tau_S)^N. \quad (3)$$

The marked STA successfully transmits a packet in a given slot, if it chooses this slot for transmission, all other STAs and the relay do not choose this slot, and the packet is not corrupted by noise during the transmission:

$$p_s^{(S)} = q_S \tau_S (1 - \tau_R)(1 - \tau_S)^{N-1}. \quad (4)$$

If the marked STA chooses a given slot for transmission, the transmission attempt is unsuccessful with the probability

$$p_c^{(S)} = 1 - q_S (1 - \tau_R)(1 - \tau_S)^{N-1}. \quad (5)$$

The probabilities of the relay's successful slot and unsuccessful transmission depend on the scenario. When the relay and a STA transmit packets simultaneously, the relay's transmission attempt is always unsuccessful in Scenario A, but it is successful with probability  $q_R$  in Scenario B. Hence, for Scenario A:

$$p_s^{(R)} = q_R \tau_R (1 - \tau_S)^N, \quad (6)$$

$$p_c^{(R)} = 1 - q_R (1 - \tau_S)^N, \quad (7)$$

while for Scenario B:

$$p_s^{(R)} = q_R \tau_R, \quad (8)$$

$$p_c^{(R)} = 1 - q_R. \quad (9)$$

Following [7, p. 539], we calculate how much virtual slots a STA spends to perform transmission attempt and find  $\tau_S$ :

$$\tau_S = \frac{1}{1 + \frac{W_{min}-1}{2} + p_c^{(S)} \cdot \frac{W_{min}}{2} \sum_{i=0}^{\log_2(\frac{W_{max}}{W_{min}})-1} (2p_c^{(S)})^i}. \quad (10)$$

It remains to find  $\tau_R$ . Depending on whether TXOP sharing is used or not, and whether the relay has always a packet for transmission or not, we have 3 cases:

- 1) If the relay is in saturation, we find  $\tau_R$  similarly to  $\tau_S$ :

$$\tau_R = \frac{1}{1 + \frac{W_{min}-1}{2} + p_c^{(R)} \cdot \sum_{i=0}^{\log_2(\frac{W_{max}}{W_{min}})-1} (2p_c^{(R)})^i}. \quad (11)$$

- 2) If the relay is not in saturation (it receives less packets from the STAs than it could transmit in saturation) and TXOP sharing is not used, the relay transmits all packets received from STAs:

$$Np_s^{(S)} = p_s^{(R)}. \quad (12)$$

Using equations (6) or (8) and (4), we can find  $\tau_R$  depending on the considered scenario.

- 3) If the relay is not in saturation and TXOP sharing is used, after performing backoff it transmits a previously received packet which has not been successfully delivered during a shared TXOP:

$$Np_s^{(S)}(1 - q_R) = p_s^{(R)}. \quad (13)$$

Using equations (6) or (8) and (4), we can find  $\tau_R$  depending on the considered scenario.

To find network throughput  $S_{leg}$  without TXOP Sharing (1), we firstly assume that the relay is in saturation and solve the system of equations (3)–(11), using equations (6) and (7) if we consider Scenario A, and equations (8) and (9), otherwise. If for found values  $p_s^{(R)}$  and  $p_s^{(S)}$ , inequality

$$Np_s^{(S)} > p_s^{(R)} \quad (14)$$

holds, then our assumption is correct. Otherwise, we solve the system of equations (3)–(10) and (12). After that, we find the throughput according to (1).

The network throughput  $S_{TS}$  with TXOP sharing (2) is obtained similarly, using equation (13) instead of (12) and

$$Np_s^{(S)}(1 - q_R) > p_s^{(R)} \quad (15)$$

instead of (14).

#### IV. NUMERICAL RESULTS

In this Section, we use the developed model to compare the throughput of the network shown in Fig. 1, when the legacy packet transmission or the TXOP sharing is used.

We assume that the packet payload is  $d = 100$  bytes. All STAs and the relay use the default set of contention window parameter values:  $W_{min} = 16$ ,  $W_{max} = 1024$ . In IEEE 802.11ah, the duration of an empty slot is  $\sigma = 52\mu s$ . Without loss of generality, we assume that the most robust MCS0 is used and transmission is performed in a 2MHz channel.

We apply the model to find how the throughput of the considered network depends on the number of STAs and the chosen mode of transmission. Analytically obtained numerical results are shown in Fig. 3. Specifically, the figure shows a set of curves: for the legacy relaying (“Leg”), TXOP sharing with explicit ACK (“E-TXOP”) and implicit ACK (“I-TXOP”) in Scenario A (“Sc.A”) and Scenario B (“Sc.B”),

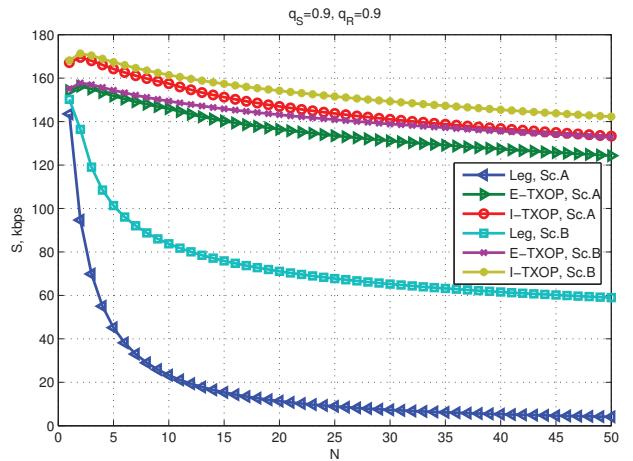


Figure 3. Dependence of network throughput  $S$  on  $N$  at MCS0

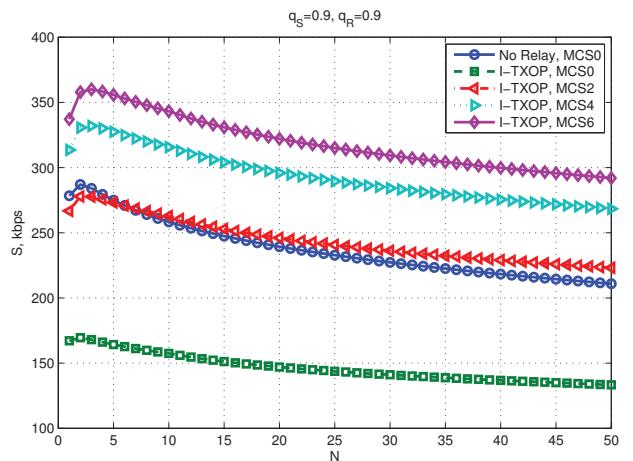
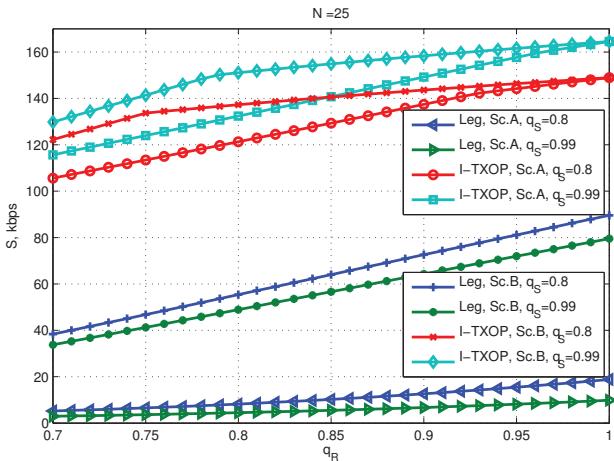


Figure 4. Comparison of the I-TXOP and the direct transmission in Scenario A

To validate the analytical model, we have also implemented the TXOP sharing mechanism in the NS-3 [12] network simulator, which implements PHY and MAC layer of the IEEE 802.11 standard [1] quite accurately. Experiments show that our analytical model gives very precise results, with error below 3% in the considered scenarios.

Fig. 3 show that the legacy relaying in Scenario A is very inefficient and leads to a rapid throughput decrease to 0. This happens because STAs perform many transmission attempts between two consecutive transmission attempts of the relay, which increases the packet delivery time and decreases the throughput. More than that, with the increase of the number of STAs, the failure probability of relay’s transmission significantly rises, which increases the average number of attempts needed for packet delivery.

In opposite to Scenario A, in Scenario B, the failure probability of relay’s transmission is significantly lower, because STAs’ transmissions do not corrupt the packet transmitted by the relay. As a result, the relay delivers the previously received

Figure 5. Dependence of network throughput  $S$  on  $q_S$  and  $q_R$ 

packet to the AP much faster, which leads to much higher throughput compared to Scenario A.

The usage of TXOP sharing increases the throughput compared with the legacy relaying. The huge gain is achieved because TXOP sharing significantly reduces the average time needed to forward a packet from a STA to the AP.

The difference in throughput values with explicit and implicit versions of TXOP sharing is about 10% for short packets typical for IoT and decreases with the increase of data packet size  $d$ .

However, in Scenario A, the STAs may send packets directly to the AP without using the relay. Fig. 4 compares the throughput when STAs directly transmit packets to the AP or via the relay, using the implicit TXOP sharing. In this experiment, we assume that STAs are located at the edge of the AP's coverage zone and can use only MCS0 for the direct transmission to the AP. In the same time, if a STA transmits a packet via the relay, both the STA and the relay can use an MCS with a higher transmission rate depending on the network topology. The results show that if channel conditions allow STAs and the relay to use an MCS faster than MCS2, the usage of the I-TXOP leads to higher network throughput comparing to the direct transmission.

Fig. 5 shows the dependence of the network throughput on probabilities of successful transmission attempt of a STA ( $q_S$ ) and the relay ( $q_R$ ). Since curves "I-TXOP" and "E-TXOP" are very close to each other, we do not show E-TXOP curves.

As expected, the rise of  $q_R$  increases throughput. Surprisingly, the increase of  $q_S$  can negatively affect the network throughput, if the legacy relaying is used: compare "Leg" curves with  $q_S = 0.8$  and  $q_S = 0.99$ . In particular, if the relay is saturated (with  $N \geq 2$  for legacy relaying), the growth of  $q_S$  causes the increase of the number of STA transmission attempts per slot, because the average contention window  $W$  of STAs reduces. As a result, packets of the relay collide with packets of STAs more frequently and the network throughput decreases. In contrast to the legacy relaying, if the TXOP

sharing is used, the throughput always increases with the growth of the  $q_S$ , because most of the packets are forwarded by the relay in STAs' TXOPs.

## V. CONCLUSION

In this paper, we have developed the first analytical model of the TXOP sharing mechanism in the 802.11ah networks. With this model, we have shown that TXOP sharing significantly improves the network throughput. We found that, surprisingly, in a saturated network without TXOP sharing the throughput may decrease with the growth of the probability of STA successful transmission attempt. Such an effect is not inherent in TXOP sharing. Although in this paper we have considered 802.11ah network with only one relay, in future work we plan to extend this study for the case of networks with several relays and hidden STAs.

## ACKNOWLEDGEMENTS

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