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IEEE 802.11aa Intra-AC Prioritization – A New Method of Increasing the Granularity of Traffic Prioritization in WLANs

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***Abstract*—Audio-video streaming in Wi-Fi (IEEE 802.11) wireless local area networks (WLANs) has recently attracted a lot of attention. In order to increase the granularity of traffic prioritization and quality of service (QoS) support defined by EDCA, intra-access category prioritization has recently been introduced in the IEEE 802.11aa amendment. In this paper, we present novel results which show how the new mechanism impacts the performance of an access point (AP). Additionally, we propose a wireless credit-based shaper algorithm (WCBSA), a version of CBSA adjusted to the wireless environment. We also analyze how the different settings of WCBSA impact the prioritization of traffic streams. Finally, we compare the operation of 802.11aa intra-access category prioritization with the legacy inter-access category prioritization defined by EDCA.**

***Keywords*—IEEE 802.11aa, credit-based shaping, intra-AC prioritization, internal collision, EDCA, Wi-Fi**

I. INTRODUCTION

The transmission of audio-video streams over wireless local area networks (WLANs) has become popular and profoundly contributes to Internet traffic. As a result, a number of QoS-aware MAC protocols have been proposed in the literature to provide support for this type of transmission [1]. Moreover, standardization bodies have tried to improve the effectiveness and QoS support at the MAC layer in IEEE 802.11 [2]. The first QoS successor to the original distributed coordination function (DCF) was the enhanced distributed channel access (EDCA) function, which mapped traffic streams to four access categories (ACs). However, EDCA did not support differentiation of streams within a single AC. As a remedy to this and other problems, the IEEE 802.11aa amendment has recently been published [3].

IEEE 802.11aa defines mechanisms to improve audio-video streaming over WLANs: groupcast with retries, the stream classification service, overlapping basic service set management, interworking with the IEEE 802.1Q stream reservation protocol, and intra-access category (intra-AC) prioritization. In this paper, we focus on intra-AC prioritization in which frames are selected for transmission using a credit-based transmission selection algorithm (cf. Section II) using two transmission queues: primary and alternate.

There have been several surveys describing the new features of IEEE 802.11aa [4]–[7]. Other papers focus on reliable multicast mechanisms [8]–[11] or provide mathematical analysis of the intra-AC prioritization [12]. Our paper distinguishes itself from the state of the art in that we show through extensive simulations how the intra-AC prioritization impacts the performance of a WLAN (cf. Section IV). Since, the infrastructure network is the default topology considered in IEEE 802.11aa, we focus on the impact of this new QoS feature on the performance of an access point (AP). In particular, we show how the intra-AC prioritization differs from the legacy inter-AC prioritization. We also illustrate how the increased granularity of traffic prioritization can be employed to increase the throughput of VI streams. Finally, we comment on the behavior of WCBSA, a version of the credit-based shaper algorithm adjusted to the wireless environment. To achieve our goal, we have implemented the intra-AC prioritization together with WCBSA in ns-3 [13] (cf. Section III). To our best knowledge this is the first such implementation. We hope that our pioneer work on intra-AC prioritization will contribute to the understanding and successful deployment of IEEE 802.11aa in future WLANs.

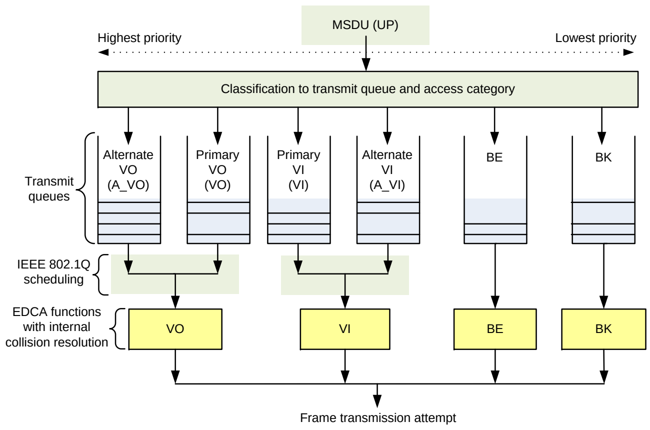


Fig. 1. Traffic prioritization in IEEE 802.11aa.

II. INTRA-AC PRIORITIZATION WITH THE WIRELESS CREDIT-BASED SHAPER ALGORITHM

The intra-AC prioritization mechanism extends the operation of legacy EDCA by defining alternate MAC queues for the VO and VI ACs to obtain a finer-grained prioritization between individual audio and video streams. In other words, a more important video stream (e.g., video conference) and a less important video stream (e.g., video streaming) can be treated with different priorities and the quality of the latter transmission can be decreased in order to assure appropriate QoS for the former. IEEE 802.11aa defines a total of six transmission queues: two VO (primary VO and alternate A_VO), two VI (primary VI and alternate A_VI), BE, and BK (Fig. 1). All six queues are derived from the IEEE 802.1D user priorities (UPs) [14]. Frames belonging to competing queues within an AC are selected using a transmission selection algorithm, which must be configured so that frames belonging to the queue with the higher UP are selected with a higher probability than from the lower priority queue. The selection of frames for transmission is done according to either the strict priority algorithm (SPA) or the credit-based shaper algorithm (CBSA), defined in IEEE 802.1Q for two queues. SPA is the default transmission selection algorithm, which gives absolute priority to the high priority queue. CBSA is an optional algorithm which is more complex but allows flexible bandwidth allocation for different queues. In the following we briefly describe the operation of CBSA, which is investigated in this paper. For further details on SPA and CBSA we refer the reader to [15]. Having been scheduled, frames are mapped to four independent EDCA functions and the actual frame transmission is organized using procedures defined in [2].

In CBSA, frame selection is based on an internal *credit* parameter. A frame belonging to a given queue is selected only if (i) for the primary queue *credit* is non-positive and (ii) for the alternate queue *credit* is either positive or when *credit* is equal to zero and the primary queue is empty. The *credit* value is calculated based on two external parameters: *portTransmitRate*—the transmission rate, in bits per second, supported by the underlying MAC service, and *idleSlope*—the rate of change of *credit*, in bits per second, when the value of *credit* increases. The latter determines the maximum portion of *portTransmitRate* available for the transmission of frames stored in the alternate queue. Additionally, *sendSlope*, an internal parameter, determines the rate of *credit* change, in bits per second, when the value of *credit* decreases:

$$sendSlope = idleSlope - portTransmitRate. \quad (1)$$

Credit is increased with a rate of *idleSlope* (a) during the transmission of a frame from the primary queue and (b) when there is no transmission while *credit* is negative. *Credit* is decreased with a rate of $sendSlope$ during the transmission of a frame from the alternate queue. If $credit$ is positive and the alternate queue is empty then it is reset to zero.

Additionally, the following auxiliary values are defined in the IEEE 802.1Q standard for CBSA: *loCredit*—the minimum value that can be accumulated in the *credit* parameter:

$$loCredit = maxFrameSize \times \frac{sendSlope}{portTransmitRate}, \quad (2)$$

and *hiCredit*—the maximum value that can be accumulated in the *credit* parameter:

$$hiCredit = maxInterferenceSize \times \frac{idleSlope}{portTransmitRate}, \quad (3)$$

where *maxFrameSize* is the maximum size of a frame that can be transmitted and *maxInterferenceSize* is the maximum size of a burst of traffic that can delay a frame transmission.

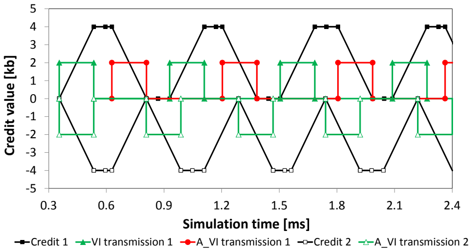


Fig. 2. Justification of the adjustment period requirement. In the first setting, frames are transmitted from both the primary and alternate VI queues (*VI transmission 1* and *A_VI transmission 1*). In the second setting, frames are transmitted only from the alternate queue (*A_VI transmission 2*). WCBSA without the adjustment period is used.

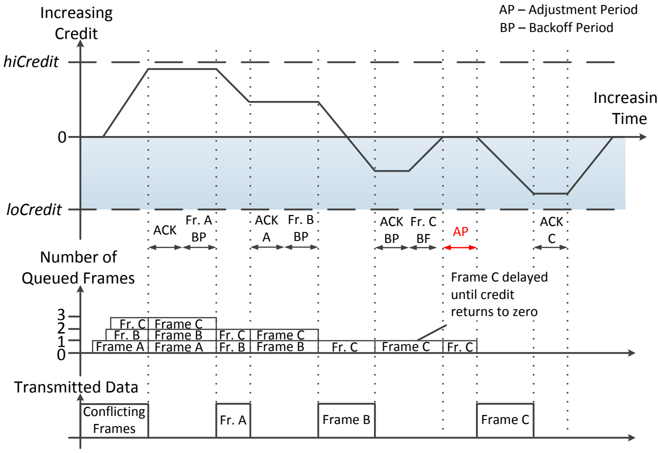


Fig. 3. Credit-based shaper algorithm operation for three frames (A, B, and C) queued in the alternate queue during the transmission of conflicting traffic.

A. *Interpretation of CBSA*

The definition of CBSA in IEEE 802.1Q is very general, i.e., it is only straightforward for wired networks, and its final shape for the wireless environment is left open for CBSA developers. Therefore, in order to provide the best fractional throughput division between primary and alternate queues within an AC we propose to change the *credit* value only during the actual frame transmission in the wireless medium and keep the counter stopped during certain periods (characteristic to the contention-based channel access), during which transmission of frames from either queue (primary or alternate) is not possible. From the perspective of a given wireless station these periods are the following: busy medium and backoff countdown while medium access is requested, acknowledgment reception, and frame retransmission. Additionally, the *credit* counter should stop when a frame is selected for transmission and, during the actual frame transmission, the *credit* should change according to the legacy CBSA rules. Finally, to provide linear limitation of throughput available for the low priority queue, when the high priority queue is empty, each low priority frame selected for transmission should additionally be delayed after the *credit* counter returns to zero. This *adjustment period* is introduced to compensate backoff and acknowledgment procedures, encountered by high priority frames.

The graphical justification of the compensation requirement is illustrated in Fig. 2. It compares two cases of the *credit* value changes for WCBSA without the adjustment period when *idleSlope* = 50%. The former (*credit* 1) is connected with the transmissions performed by the primary and alternate queues under saturation. The latter (*credit* 2) shows the operation of the algorithm when only the alternate queue is saturated and the primary one is empty. When both queues are loaded, *credit* 1 changes only during the actual frame transmissions. Additionally, after each transmission, the acknowledgment and backoff procedures take place. In the second case, alternate frames are delayed only until *credit* 2 returns to zero. After that, the frames are transmitted immediately. As a result, without the adjustment period, the alternate queue obtains higher throughput when the primary queue is empty. The application of the adjustment period enables more precise throughput control. The proposed adjustment period is calculated as follows:

$$T_{\text{adjustment}} = \left(\frac{100\%}{idleSlope[\%]} - 1\right) \times T_1 + T_2 \qquad (4)$$

where $T_1 = 2 \times \text{SIFS} + T_{\text{SlotTime}}\left(\text{AIFSN[AC]} + \frac{CW_{min}[\text{AC}]}{2}\right) + T_{\text{ACK\_duration}}$ and $T_2 = \text{SIFS} + T_{\text{SlotTime}}\big(AIFSN[\text{AC}] + \text{rand}\,(0, CW[\text{AC}])\,\big)$.

Fig. 3 presents the overall operation of the proposed *Wireless Credit-Based Shaper Algorithm* (WCBSA) for three frames queued in the alternate queue.

III. SIMULATION SETTINGS

We have implemented the intra-AC prioritization feature together with WCBSA in the ns-3.17 simulator. To our best knowledge this is the first such implementation. Additionally, the Wi-Fi implementation was improved to provide better compliance with the IEEE 802.11 standard. The most important changes include: the correction of the acknowledgment and retransmission mechanisms and the behavior of EDCA backoff counters. Additionally, the simulator was fixed with respect to the MSDU lifetime limit, retry counters, and increase of the contention window to make it standard-compliant.

The simulation parameters are presented in Table I. The 802.11a PHY layer was chosen and the standard EDCA parameters were set for each AC. Traffic was transmitted as constant bit rate (CBR) streams using UDP. The wireless channel introduced no errors. Finally, in our simulations the *idleSlope* parameter was given in % (and not Mbps), i.e., it represented the fraction of *portTransmitRate* available for the alternate queue and was calculated as

$$idleSlope[\%] = \frac{idleSlope\ [\text{Mbps}]}{portTransmitRate\ [\text{Mbps}]} \times 100\%. \qquad (5)$$

The descriptions of configuration scenarios and their goals are given in Table II. They constitute a wide range of examples of intra-ac prioritization for an AP.

TABLE I. SIMULATION SETTINGS

Paramter	**Value**	**Paramter**	**Value**
RTS/CTS, TXOPLimit	Turned off	Queue size	400 frames
Operation mode	Ad-hoc	MSDU Lifetime	500 ms
SIFS	16 μs	Slot time	9 μs
Preamble length	16 μs	PLCP header length	4 μs
DATA payload	1000 B	PHY layer	OFDM (802.11a)
Data rate	54 Mbps	Basic rate	6 Mbps
Traffic type	CBR	Transport protocol	UDP
Parameter		**Value**	
CW$_{min}$ {VO, VI, BE, BK}		{3, 7, 15, 15}	
CW$_{max}$ {VO, VI, BE, BK}		{7, 15, 1023, 1023}	
AIFSN {VO, VI, BE, BK}		{2, 2, 3, 7}	

TABLE II. CONFIGURATION SCENARIOS

Scenario A: The AP is a source of six traffic streams (2×VO, 2×VI, BE, BK) with different intensity (0 Mbps – 25 Mbps). Two configurations are considered:

- C. 1 Frames belonging to six queues compete within the AP to be selected for transmission. One of the VO (VI) streams is handled by the primary VO (VI) queue and the other VO (VI) stream is handled by the alternate VO (VI) queue. *IdleSlope* values are set to 25% for the VO and A_VI queues.
- C. 2 EDCA is used to transmit the considered traffic streams.

Goal: Illustration of the intra-ac prioritization, comparison with the legacy inter-ac prioritization, validation of the WCBSA implementation.

Scenario B: An AP is a source of low priority VO and VI traffic streams of different intensity (0 Mbps – 30 Mbps). Four configurations are considered:

- C. 1 *IdleSlope* of VO and A_VI queues are set to 25%,
- C. 2 *IdleSlope* of A_VI is set to 25% and it is turned off for VO (i.e., EDCA AC VO is used for transmission of VO frames),
- C. 3 *IdleSlope* of VO is set to 25% and it is turned off for VI (i.e., EDCA AC VI is used for transmission of VI frames), and
- C. 4 EDCA VO and VI ACs are used for transmission of VO and VI frames, respectively.

Goal: Illustration of the impact of AC VO and AC VI throughput control on the AP performance.

Scenario C: The AP is a source of four traffic streams (VO, VI, BE, BK). The intensity of each stream is set to 30 Mbps. Only the primary VO and VI queues are used for VO and VI data transmission (i.e., the alternate queues A_VO and A_VI are not used in this configuration). *IdleSlope* of the primary VO queue changes from zero to 100%.

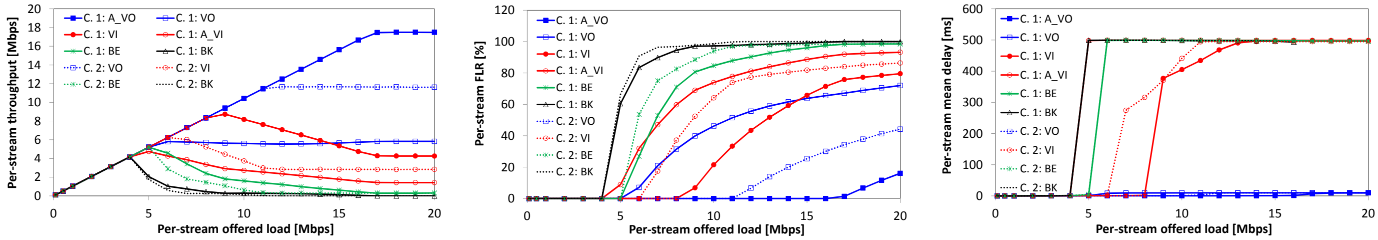
Goal: Illustration of the impact of AC VO throughput control on the throughput of other ACs.

Scenario D: The analyzed network topology is presented in Fig. 4. The AP is configured to use 802.11aa with WCBSA and *idleSlope* $= 25\%$. There are two types of stations: A type ($\{\text{STA}_1 \ldots \text{STA}_n\}$) and B type ($\{\text{STA}_{n+1} \ldots \text{STA}_{2n}\}$). Three configurations are considered:

- C. 1 Bidirectional transmission of VI streams between AP and A-type stations, directional transmission of A_VI streams from AP to each B-type station.
- C. 2 Bidirectional transmission between AP and A-type stations (VI streams) and between AP and B-type stations (A_VI streams). Stations use EDCA.
- C. 3 Bidirectional transmission between AP and A-type stations (VI streams) and between AP and B-type stations (A_VI streams). Stations use 802.11aa with WCBSA and *idleSlope* $= 25\% \times \frac{1}{n}$.

Goal: Illustration of the applicability of 802.11aa in real WLANs. Illustration of the impact of external traffic on the intra-AC prioritization.

The following metrics were calculated: throughput in Mbps, frame loss ratio in % (including losses in queues and at the MAC layer) calculated as $FLR = \frac{\text{no. of received frames}}{\text{no. of generated frames}} \times 100\%$, frame delay in ms (including queuing delay and MAC transmission delay), and jitter in ms calculated as $\frac{\sum_{n=1}^{N} |\text{frame delay}(n) - \text{frame delay}(n-1)|}{N}$, where N is the number of frame transmissions. In all figures, the error of each simulation point for a 95% confidence interval did not exceed ±2%.



(a) (b) (c)

Fig. 6. The (a) throughput, (b) FLR, and (c) mean delay of each traffic stream for 802.11aa (C.1) and EDCA (C.2).

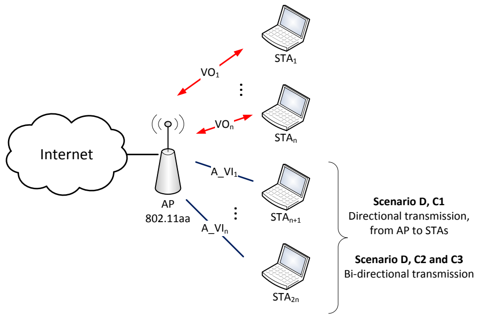


Fig. 4. Network topology in Scenario D.

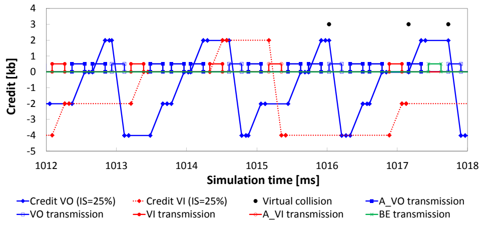


Fig. 5. Change of VO and VI queues' *credit* values for *idleSlope*[VO] = *idleSlope*[A_VI] = 25% under saturation for an exemplary time interval.

IV. RESULTS

A. Intra-AC Prioritization within the AP

Fig. 5 and 6 validate the correctness of the implementation of the intra-AC prioritization with WCBSA in ns-3 because the overall available throughput of VO and VI ACs is divided between the primary and alternate queues proportionally to the setting of the *idleSlope* parameter and the *credit* values change in accordance to the WCBSA definition given in Section II-A.

Fig. 5 shows the change of VO and VI *credits* under saturation when *idleSlope*[VO] = *idleSlope*[A_VI] = 25%. It also illustrates the frame transmissions from different queues and virtual collisions in order to explain the VO (VI) *credit* value changes. In this configuration the throughput of BK equals zero, therefore, it is not presented in the figure.

Fig. 6(a) shows the impact of intra-AC prioritization with WCBSA on throughput control. The highest priority queue A_VO has the highest throughput. Thanks to the setting of *idleSlope* = 25%, under saturation, the throughput of the primary VO queue is lower than the primary VI queue up to 14 Mbps of the per-stream offered load. This is an interesting feature of 802.11aa because by an appropriate setting of the *idleSlope* parameters it is possible for a VI stream to obtain higher throughput than a VO stream. This was not possible with EDCA if each AC had the same load. The new feature is important because typically the overall throughput of all VO streams transmitted in WLANs is much lower than the throughput of VI streams. The changes in FLR and mean frame delay (Fig. 6(b) and 6(c), respectively) are in line with the throughput changes for all six 802.11aa queues. Additionally, in comparison to EDCA, 802.11aa assures finer-grained prioritization of traffic steams. High priority VO (VI) traffic streams of up to 17 Mbps (8 Mbps) can obtain satisfactory QoS (i.e., FLR and overall delay close to zero and jitter < 1 ms)[1]. The low priority VO (VI) traffic streams perform well up to 5 Mbps (4 Mbps). For EDCA, the performance of the VO (VI) traffic streams is satisfactory up to 11 Mbps (6 Mbps).

B. Impact of VO/VI Throughput Control on AP Performance

For the first configuration, the performance of both AC VO and AC VI is the same. Under saturation the throughput of both ACs is equal to 6.7 Mbps (Fig. 7(a)). The largest preference of VO AC over VI AC is for the second configuration. Additionally, in comparison to the legacy EDCA (i.e., fourth configuration), the performance of VO is only slightly better while the performance of VI is much worse. For EDCA, VO (VI) traffic streams of up to 22 Mbps (13 Mbps) and for 802.11aa, VO (VI) traffic streams of up to 24 Mbps (8 Mbps) obtain satisfactory QoS. For the third configuration, the performance of AC VI is much better than that of AC VO. AC VI performs satisfactory up to 18 Mbps and AC VO up to 9 Mbps of per-queue generated traffic. Such inverse behavior of ACs in comparison to legacy EDCA may be helpful in Wi-Fi deployments because usually, as already mentioned, AC VO (e.g., audio streaming) will not require as high throughput as AC VI (e.g., video streaming).

C. Impact of VO Throughput Control on Other ACs

Fig. 8 illustrates that by limiting VO throughput, the remaining ACs can obtain a different share of the available bandwidth. It also shows that the credit-based shaping defined in 802.1Q is not always sensitive enough, i.e., the changes of the *idleSlope* parameter do not impact the throughput values, which leads to unexpected behavior. We show this behavior on the WCBSA example but it should be kept in mind that it is not implementation-specific and alternative CBSA interpretations, being in line with the 802.1Q guidelines, would

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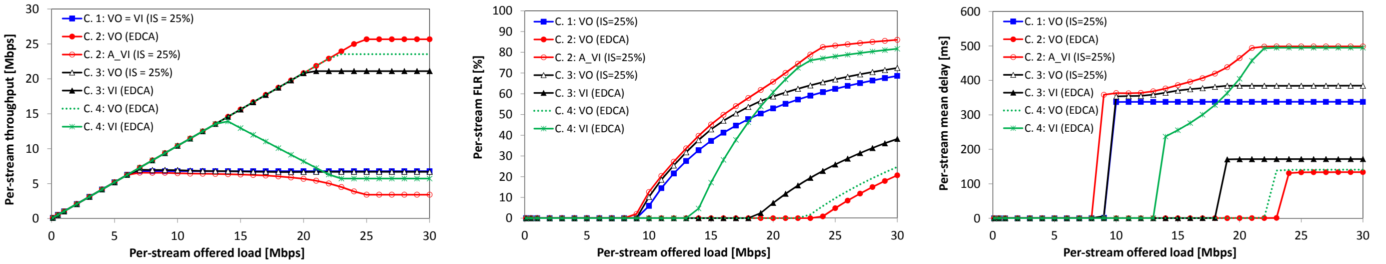
[1] In all analyzed scenarios the jitter of VO and VI ACs is less than 2 ms when WCBSA is used.

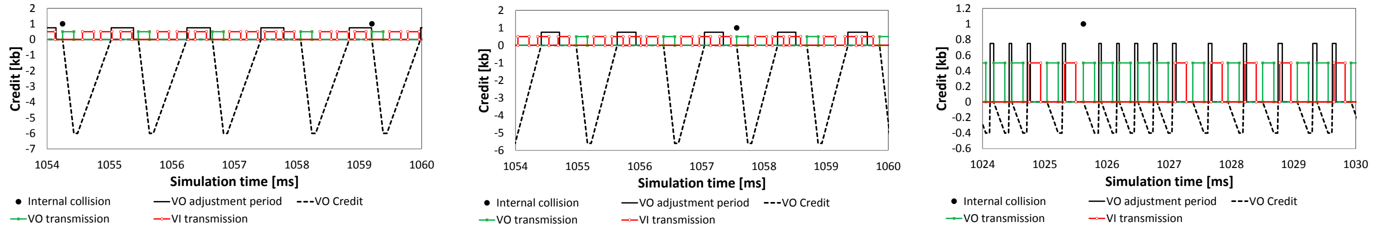


(a)

(b)

(c)

Fig. 7. The impact of VO and VI throughput control on the AP performance: (a) throughput, (b) FLR, and (c) mean delay of each traffic stream.



(a)

(b)

(c)

Fig. 9. Change of *credit* for the VO queue and different *idleSlope* values: (a) 25%, (b) 30%, and (c) 95%.

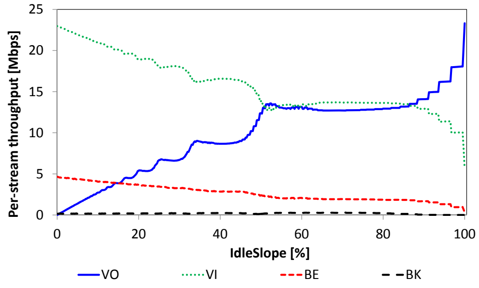


Fig. 8. Impact of VO throughput control on the performance of competing queues (VI, BE, BK): per-traffic stream throughput.

give qualitatively similar results. This is because CBSA is a local algorithm and, therefore, it is able to control traffic only within an AC in a particular station and does not have any impact on other ACs and/or other stations.

For WCBSA, the described behavior occurs, e.g., when *idleSlope* $= (25\%, 30\%)$. The explanation of its occurrence is given in Fig. 9. The figure illustrates the changes of *credit* for the VO queue for an exemplary time interval and shows how VI transmissions impact the VO *credit* changes. With the increase of the VO *idleSlope*, the probability of VO transmission in most cases increases (Fig. 8). However, for certain *idleSlope* values, e.g., *idleSlope* $= (25\%, 30\%)$, the probability of a VO frame transmission does not change because of the same probability in the following case: *credit* is zero and there is an ongoing VI transmission which blocks the VO transmission (Fig. 9). As a result, both ACs compete after the VI transmission as in EDCA. Fig. 9 additionally shows the impact of virtual collisions on the MAC performance. As defined in EDCA, when VO and VI frames collide internally, the VO frame is transmitted and the VI frame chooses a new backoff value. Another important observation from Fig. 8 is that under saturation the performance of the primary VO queue is always worse than that of the legacy VO AC for EDCA. If *idleSlope*=100% then the throughput of the primary VO queue is not limited, therefore, its performance is equal to that of EDCA AC VO. From the above observations, we conclude that a self-configuration mechanism should be used to tune the *idleSlope* setting adequately to current network conditions instead of setting it to a static value.

D. Applicability of 802.11aa in Real WLANs

In the last scenario we analyze the applicability of 802.11aa in real WLANs for an exemplary setting of WCBSA in an AP. When the AP is a source of n bidirectional video conferences (VI) between the AP and a group of n stations (type A stations) and additionally there are n video streams (A_VI) directed to n other stations (type B stations), intra-AC prioritization works correctly (Fig. 10). In comparison to the legacy EDCA, a larger number of high priority VI streams can be served without the loss of their quality (Fig. 10(a))[2]. At the same time, the number of correctly served A_VI streams drops. With an additional admission control mechanism (i.e., dropping unacceptable A_VI streams or lowering their bitrate), the network performance can become even more satisfactory.

In Fig. 10(b), we show what would happen if a network administrator decided to replace an old AP (supporting EDCA) into a new one (supporting 802.11aa) and the stations would still use EDCA. We analyze the network with symmetrical traffic to/from the AP. Interestingly, the performance of a network with the 802.11aa AP is worse than with the EDCA AP. The large number of physical collisions does not allow to satisfactorily serve a larger number of primary VI streams compared to an EDCA network, even if the throughput of A_VI streams is limited by WCBSA.

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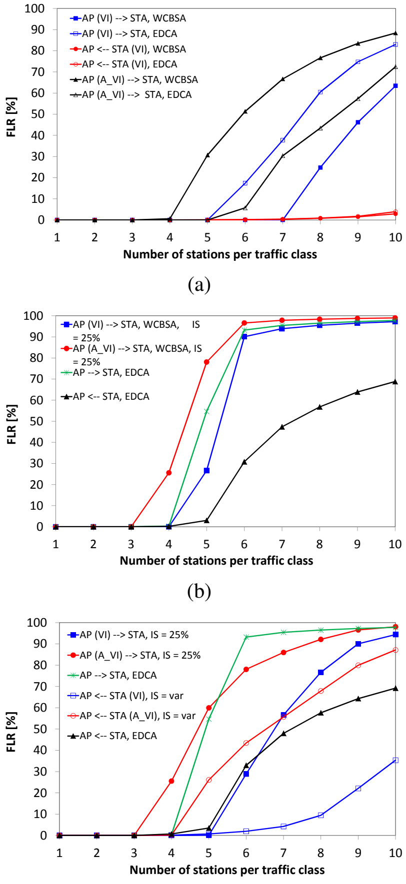
[2] Due to space limitations we present only figures showing the frame loss ratio, as the most important in our analysis.



(a)

(b)

(c)

Fig. 10. The impact of external traffic on intra-AC prioritization. Scenario D: per traffic stream frame loss ratio as a function of the number of stations per traffic class for (a) C1, (b) C2, and (c) C3.

The network administrator can configure the AP to use WCBSA with *idleSlope* $= 25\%$ and the B-type stations (transmitting A_VI streams) to use WCBSA with *idleSlope* $= 25\% \times \frac{1}{n}$ in order to limit the uplink and downlink traffic symmetrically. As a result, in comparison to EDCA, a larger number of high priority VI streams (exchanged between the AP and the A-type stations) is served with good quality thanks to either sacrificing the number or lowering the bitrate of the low priority A_VI streams (Fig. 10(c)).

The final conclusion for the above three configurations is that the intra-ac prioritization introduced solely in an AP does not give satisfactory results in case of symmetrical traffic. Only if the amount of traffic transmitted in the upstream direction (to the AP) is meaningfully lower than in the downlink direction (from the AP), the intra-ac prioritization introduced solely in the AP (and not in the wireless stations) works correctly.

V. CONCLUSIONS

The intra-AC prioritization feature defined in the recent IEEE 802.11aa amendment, in comparison to EDCA, provides a method for finer-grained prioritization of multimedia traffic. In this paper, we have presented the first implementation of intra-AC prioritization together with the WCBSA transmission selection procedure. We have illustrated the behavior of the new feature and compared its operation with that of legacy EDCA. Additionally, we have shown how the finer-grained prioritization can be employed in order to improve video streaming in real WLANs. Finally, we have commented on the credit-based shaper behavior and its insensitiveness to certain settings of the *idleSlope* parameter.

As future work we envision implementing various PHY layers. We plan to analyze the behavior of other transmission selection procedures defined in the IEEE 802.1Q standard. Based on the gathered experience we will propose alternative mechanisms. Scenarios with and without the TXOP limit, the RTS/CTS mechanism and block acknowledgment will be considered.

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