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What's New for QoS in IEEE 802.11?

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Abstract

Two amendments to IEEE 802.11 have recently been published: 802.11aa and 802.11ae. Both enhance Quality of Service (QoS) provisioning in Wi-Fi networks by providing support for multicast transmission, enhanced audio video streaming, coping with inter-network interference, and improved prioritization of management frames. The proposed solutions either extend mechanisms already existing in the standard or introduce new ones. Therefore, it is important for researchers to understand the new functionalities. To this end we provide the first description of these latest mechanisms: we present the motivation behind them, explain their design principles, provide examples of usage, and comment on compatibility issues. Finally, we identify new research challenges related to the two new amendments.

Keywords

IEEE 802.11aa, IEEE 802.11ae, Quality of Service, QoS management, groupcast, intra-access category prioritization, stream classification service, overlapping BSS management

1 Introduction

Nowadays Wi-Fi networks based on the IEEE 802.11 standard [1] have become one of the most widely used technologies to provide wireless broadband Internet access. Almost all manufactured mobile devices (laptops, smartphones, tablets, etc.) are equipped with Wi-Fi transceivers. Initially, Wi-Fi was designed as the cordless replacement for the Ethernet and only used for transmission of non-real-time traffic (Web, file sharing) with best-effort quality. The evolution of Internet applications has led to the appearance and growth of multimedia traffic (VoIP, video, online gaming etc.) which will occupy more than 60% of all Internet traffic by 2015 [2]. Unlike non-real-time traffic, multimedia traffic imposes strict Quality of Service (QoS) requirements, such as low and stable end-to-end delay, low packet loss probability, and minimal throughput. However, such QoS support was not included in the original IEEE 802.11-1999 standard [3].

During the last decade a lot of effort has been done to improve QoS support in 802.11. One of the first and most fundamental milestones was the 802.11e amendment which introduced several mechanisms for providing QoS support in single-hop networks including two coordination functions (Enhanced Distributed Channel Access — EDCA and Hybrid Coordination Function Controlled Channel Access — HCCA) as well as a complementary admission control mechanism. However, neither EDCA nor HCCA can provide absolute service guarantees, because the former is based on random contention, while the latter lacks inter-cell coordination. Another important milestone was the extension of the initial single-hop paradigm to a multi-hop one, described in the 802.11s amendment. In multi-hop networks, centralized coordination (HCCA) cannot be applied and EDCA performance is unsatisfactory [4]. Therefore, the problem of QoS provisioning in such networks is much more complex than in single-hop networks and, in fact, has not been completely solved yet. The first step towards resolving this problem was the introduction of a new coordination function, Mesh Coordination Function Controlled Channel Access (MCCA), which allows reserving channel resources in a distributed manner and, in principle, can be used for QoS provisioning in multi-hop networks.

A few years ago, IEEE recognized that several challenges need to be addressed (Table 1) for 802.11 to meet the fast-growing market demands. Among the shortcomings of the IEEE 802.11 standard was the lack of mechanisms for the prioritization of different audio video (AV) streams which belong to the same access category (AC). For example, consider a videoconference and TV broadcast which are both sent using the video AC. Since these streams have different QoS requirements they should be served with different priorities. Additionally, the 802.11 standard did not include a mechanism for the reliable transmission of multicast streams. To address these issues, a new task group (802.11aa) was created to develop a set of enhancements for robust AV streaming. Additionally, 802.11aa addresses the problem of inter-network interference caused by today’s large deployment of 802.11 networks.

A separate problem that has been recognized is related to management frames. The number of management frame types in the IEEE 802.11 standard has greatly increased from its initial release (in 1999) to its current revision (from 2012). According to this current revision, all management frames are transmitted with the highest priority. This can interfere with the transmission of multimedia traffic. Therefore, the 802.11ae task group has developed mechanisms for the flexible prioritization of such frames.

In this tutorial, we would like to provide the first description of the new QoS solutions introduced in 802.11aa [9] and 802.11ae [10]. Thanks to this tutorial, researchers and engineers will be able to easily understand the new mechanisms (Sections 3 and 4) as well as become familiar with the areas left open by the amendments (Section 5). Therefore, they will be able to provide new scientific contributions in the area of QoS provisioning in Wi-Fi networks.

Table 1 Main challenges addressed by IEEE 802.11aa and IEEE 802.11ae

Area	Challenge in current 802.11 networks	Solution	Amendment	Described in
Multicast	Lack of reliable and scalable mechanism	Groupcast with retries	802.11aa	Section 3.1
Streaming	Lack of differentiation between AV streams	Intra-access category prioritization	802.11aa	Section 3.2
Streaming	Lack of mechanism for graceful degradation of AV stream quality	Stream Classification Service	802.11aa	Section 3.3
Interference	Large number of 802.11 deployments causes inter-network interference	Overlapping BSS management	802.11aa	Section 3.4
Management	All management frames contend with multimedia frames	Policy-based management of frame prioritization	802.11ae	Section 4

The rest of this tutorial is organized as follows. In Section 2, we describe existing QoS mechanisms standardized within 802.11e and 802.11s. In Sections 3 and 4, we present the new QoS solutions introduced in the recently published amendments (802.11aa and 802.11ae, respectively). For each new solution, we explain the motivation for introducing this functionality, describe its design principles, and provide examples of usage. Additionally, we explain how all of these solutions are backward compatible with the existing 802.11 standard. We conclude the tutorial in Section 5 where we also outline possible research directions related to QoS support in 802.11 networks.

2 Background

This section briefly covers several important features of two amendments to 802.11 released within the last several years: 802.11e and 802.11s. Both are part of the latest, unified release: 802.11-2012 [1]. The first introduced basic QoS mechanisms, while the second introduced mechanisms for supporting the multi-hop paradigm. Understanding how the mechanisms highlighted in this section operate is necessary to comprehend the latest changes to the 802.11 standard.

2.1 IEEE 802.11e

IEEE 802.11e introduces two different medium access functions: a centralized one and a distributed one. In the former (HCCA), the Access Point (AP) schedules transmissions through polling. Polling can be started by the AP at any time after a PIFS interval according to a vendor-dependent scheduling algorithm. The latter mechanism (EDCA) employs four Access Categories (ACs) that are mapped into four separate queues. Frames are classified into these categories according to their IEEE 802.1D [12] user priority (Table 2). Each AC contends for the medium using the same rules but employs different channel access parameters. Using only these parameters, EDCA cannot guarantee any throughput or delay bounds, but only performance differentiation among the categories.

Table 2 Mapping of IEEE 802.1D user priorities to IEEE 802.11e access categories and IEEE 802.11aa transmit queues

802.1D user priority	802.1D designation	802.11e access category	802.11aa transmit queue	Description
7	Network Control (NC)	VO	VO	Both time- and safety-critical, consisting of traffic needed to maintain and support the network infrastructure
6	Voice (VO)	VO	A_VO	Time-critical, characterized by less than 10 ms delay
5	Video (VI)	VI	VI	Time-critical, characterized by less than 100 ms delay
4	Controlled Load (CL)	VI	A_VI	Non-time-critical but loss sensitive, such as streaming multimedia or business-critical traffic; usually used for applications that require reservation mechanisms or admission control decisions
3	Excellent Effort (EE)	BE	BE	Also non-time-critical but loss sensitive; for best-effort services delivered to the most important customers
0	Best Effort (BE)	BE	BE	Non-time-critical and loss insensitive. This is the most common traffic type, predominant in today’s networks
2	Spare (—)	BK	BK	
1	Background (BK)	BK	BK	Non-time-critical and loss insensitive, but of lower priority than best effort; includes bulk transfers and other data transfer that are permitted on the network but that should not impact the use of the network by other users and applications

Additionally, IEEE 802.11e provides support for admission control. While the admission control algorithm is vendor-dependent, the signaling mechanisms are standardized. The QoS parameters used for characterizing a given traffic stream and deciding on its admission are referenced to as its traffic specification (TSPEC). Admission control can be used under both EDCA and HCCA. In the first case, the admitted traffic stream receives a portion of the channel resources in terms of admitted time, i.e., a maximum time interval within a one-second period in which the frames belonging to the stream can occupy the wireless medium. In the second case, since the AP coordinates channel access, an admitted flow receives the required transmission time if there are enough network resources. However, since the admission decisions are taken locally by each AP without any coordination mechanism with the neighbor cells, there is no guarantee that admitted flows will ultimately find a portion of idle channel equal to the admitted time.

2.2 IEEE 802.11s

IEEE 802.11s introduces Mesh Coordination Function Controlled Channel Access (MCCA) – a medium access function which allows stations to reserve time intervals, called MCCA opportunities (MCCAOPs), for periodic data transmission. The station that has reserved an MCCAOP is the MCCAOP owner while the station or stations that receive frames are MCCAOP responders. MCCAOP reservations are advertised within a two-hop range. During MCCAOP, the owner gets access to the channel with the highest priority. In turn, to avoid collisions, neighbors of the MCCAOP owner and responders cannot start any transmissions if they overlap with the MCCAOP. This approach allows to significantly increase the total network throughput [6] and is potentially useful for multimedia streaming with strict QoS requirements in multi-hop networks.

3 IEEE 802.11aa

The goal of the mechanisms proposed in 802.11aa is to improve multimedia streaming performance in 802.11 networks. Among the enhancements introduced are: Groupcast with Retries (GCR), intra-access category prioritization, Stream Classification Service (SCS), Overlapping Basic Service Set (OBSS) management, and interworking with the IEEE 802.1Q Stream Reservation Protocol (SRP). These mechanisms, described in details below, will increase the robustness of AV streaming for both consumer and enterprise applications.

3.1 Groupcast with Retries

Groupcast reduces network traffic by delivering the same data stream to multiple recipients simultaneously. Various applications (e.g., TV and radio broadcasting, gaming, videoconferencing), which use groupcast transmission techniques, have already crowded the market. The current 802.11 standard defines two methods of transmitting group addressed frames: broadcast and directed multicast (group addressed frames are converted to individually addressed frames). The first solution is unreliable; the second is non-scalable. Therefore, 802.11aa proposes a new mechanism called Groupcast with Retries (GCR) which makes groupcast transmissions more reliable. In particular, GCR defines two additional retransmission policies for group addressed frames: GCR Unsolicited Retry and GCR Block Ack. The groupcast originator (the station or AP providing the GCR service) decides which policy to use.

When using GCR Unsolicited Retry, the groupcast originator retransmits a data frame one or more times (subject to its lifetime limits) to increase the probability of its correct reception by stations listening to this group address (Figure 1a). In order to avoid correlated packet losses, retransmissions of the same data frame shall be performed during separate medium access attempts. GCR Unsolicited Retry is particularly suited to use with a large number of recipients as it has moderate delay, efficiency, and reliability, but high scalability.

GCR Block Ack extends the Block Acknowledgement[1] (Block Ack) [1] mechanism to group addressed frames. After initiating Block Ack agreements with each receiving station, the groupcast originator operates in the following way (Figure 1b). Having obtained access to the channel, it transmits a burst of groupcast data frames and then exchanges Block Ack Request and Block Ack frames with all groupcast recipients or with a subset of them to ascertain the data frames' reception status. This allows the groupcast originator to discover data frames that have failed to be received and to schedule their retransmission.

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[1] Instead of transmitting individual acknowledgements for each data frame, multiple data frames can be acknowledged together using a single Block Acknowledgement.

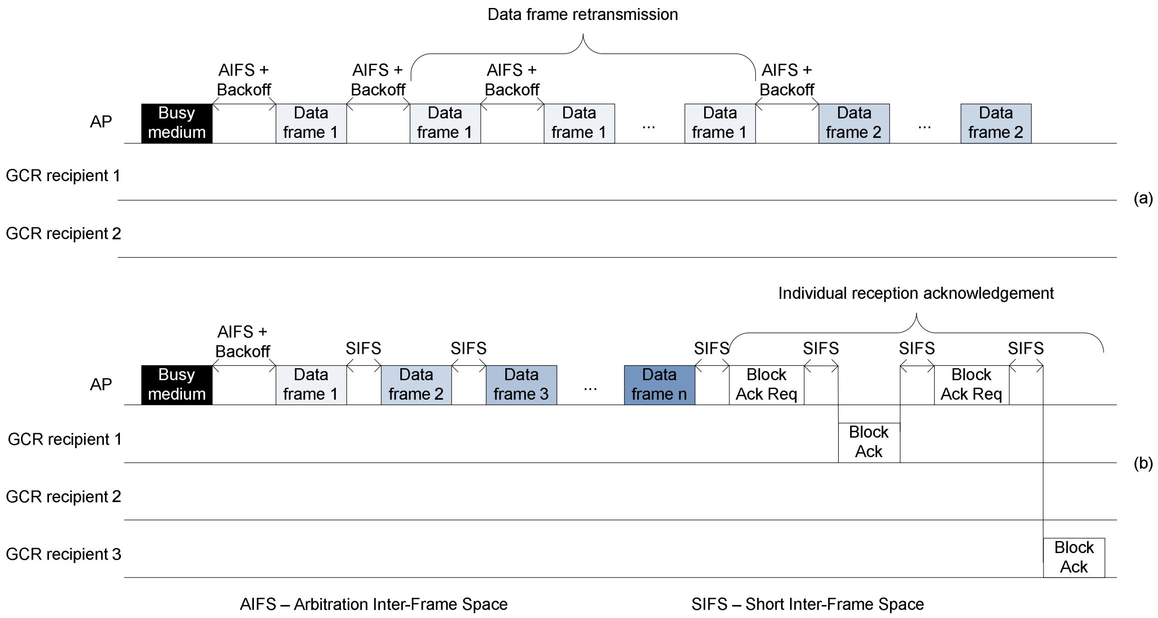

Figure 1 GCR service with (a) Unsolicited Retry or (b) Block Ack

As mentioned before, GCR Block Ack allows varying the number of groupcast recipients requested for Block Ack. However, 802.11aa does not specify which and how frequently groupcast recipients should be requested for Block Ack. It should be noticed that requesting all recipients for Block Ack may cause long transmission delays which is not appropriate for certain applications (e.g., real-time multimedia streaming) due to their strict QoS requirements, especially when the number of groupcast recipients is large.

To address compatibility issues, the specification of GCR includes a special address concealment mechanism. This mechanism is necessary, because the existing IEEE 802.11 standard implies that all group-addressed frames are transmitted without retries. On the other hand, GCR-capable stations may retransmit groupcast frames. Thus, GCR-incapable stations (i.e., legacy stations) should be protected from receiving duplicate group-addressed frames. Such frames, transmitted using either the GCR Unsolicited Retry or the GCR Block Ack retransmission policies, are sent in a special frame format[2] with the first address field set to a special GCR concealment address. The destination address in the frame contains the group address of the GCR group address that is being concealed (i.e., the same value as the destination address for non-GCR group-addressed delivery).

To show the advantages of the new methods for transmitting groupcast frames over the existing ones (Broadcast and Directed Multicast Service, DMS) consider the following example. A single AP transmits a groupcast video stream to $N = 25$ recipients using 802.11a PHY and a 54 Mb/s data rate. The video packet size is set to 1024 bytes. All recipients are divided into 3 sets and recipients of the same set have the same packet error rates (PERs): 5 recipients with PER = 0.1, 5 recipients with PER = 0.075, and 15 recipients with PER = 0.01. To meet QoS requirements for the stream, the packet loss ratio (PLR) for video packets shall be less than or equal to $p_{max} = 4\%$. We compare the Broadcast, DMS, and GCR Block Ack methods. Because 802.11aa does not specify which stations should be

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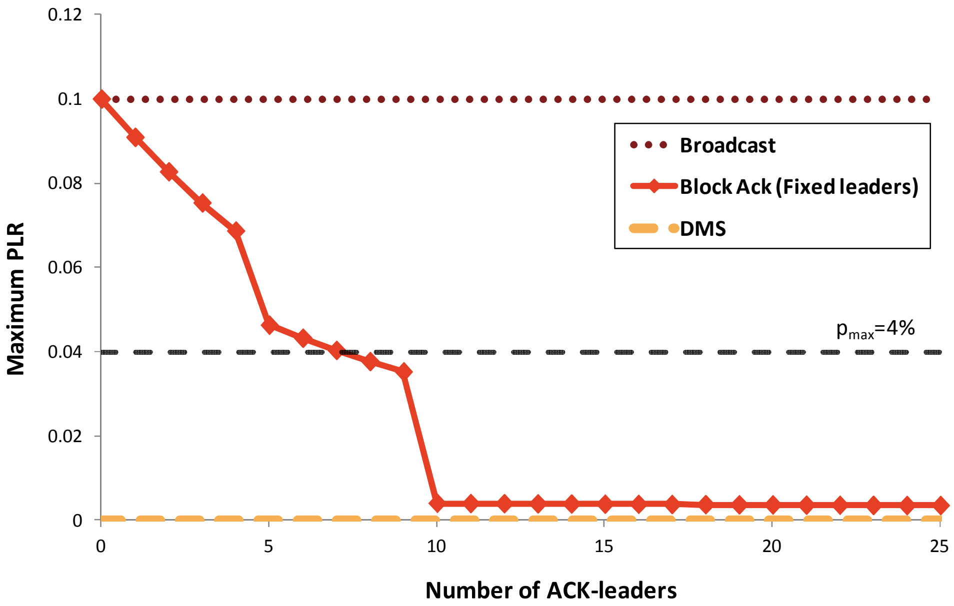
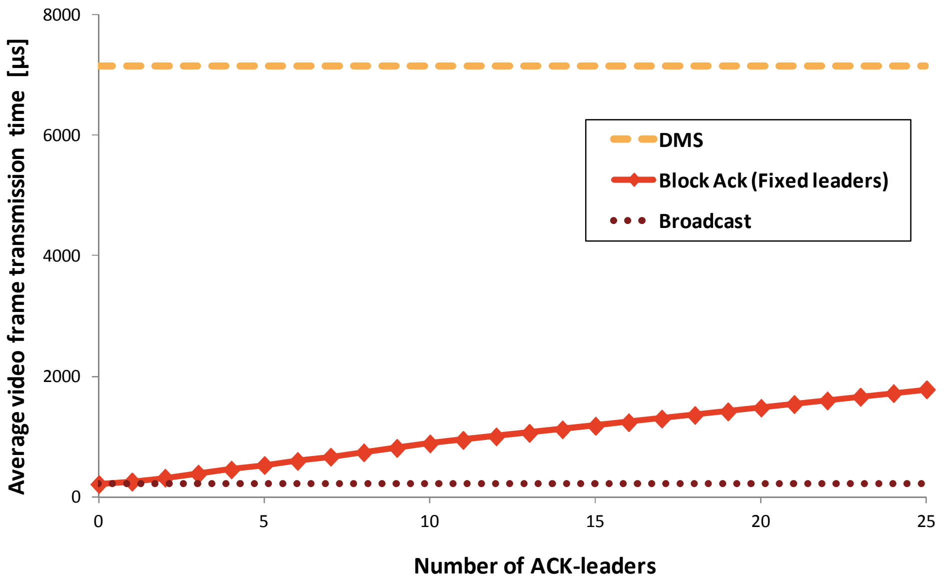
[2] This special frame format (the Aggregate MAC Service Data Unit, A-MSDU) is used since it includes an additional address field. Therefore, there is enough space for both the concealment and group addresses.

selected as ACK-leaders (i.e., which stations should be requested for Block Ack) when GCR Block Ack method is used we need to choose a method of selection. Among the several schemes proposed and compared in [8] we have chosen "Fixed-ACK leaders" for this tutorial. Using this scheme, the groupcast originator selects *J* ACK-leaders which experience the highest PER out of all *N* recipients ($J \le N$).

We compare different methods using two criteria: reliability and resource consumption. The former is measured by comparing the maximum PLR of video packets vs. the number of ACK-leaders (Figure 2a). The latter – by comparing the average time needed for the transmission of a single video frame (Figure 2b). This average time includes all data frame retransmissions as well as the transmission of control frames.



(a)



(b)

Figure 2 Comparison of multicast (a) reliability and (b) resource consumption

From the presented results we conclude that broadcast consumes the least amount of resources, but it is absolutely unreliable since each packet is transmitted only once. On the other hand, DMS is the most reliable method but consumes too much resources. Each data frame is transmitted as many times as the number of recipients which causes long transmission delay. Therefore, DMS is an ultra-reliable but non-scalable method and cannot be used in cases with a large number of recipients. In contrast to broadcast and DMS, GCR Block Ack is very flexible. By tuning the number of ACK-leaders we can meet the QoS requirements of a particular flow while consuming much less resources than using DMS. In this example, using Fixed ACK-leaders only $J_0 = 8$ recipients (out of all 25 recipients) are needed to meet the QoS requirements and the amount of resources consumed is one order less than for DMS.

3.2 Intra-Access Category Prioritization

Due to the increasing number of video streams (Cisco estimates predict that "by 2015, the world will reach 3 trillion Internet video minutes per month, which is 1 million Internet video minutes every second" [2]) there is a need for differentiation between individual AV streams. Consider an enterprise AP serving both a videoconference and a TV broadcast. With 802.11aa it is possible to serve these two video streams with different QoS using a new traffic differentiation mechanism.

This new mechanism (intra-AC traffic differentiation) extends the granularity of EDCA inter-AC traffic differentiation. It divides the transmit queues for Voice (VO) and Video (VI) ACs into two (primary and alternate) to provide differentiation between individual AV streams. Therefore, there are six transmit queues in total:

- Primary Voice (VO),
- Alternate Voice (A_VO),
- Primary Video (VI),
- Alternate Video (A_VI),
- Best Effort (BE),
- Background (BK).

These queues are derived from the IEEE 802.1D user priorities [12] as shown in Table 2[3]. The transmit queues are mapped to four independent EDCA functions (Figure 3). A dedicated scheduler is used to determine which head-of-line frames from the VO and A_VO (VI and A_VI) queues should be passed to the appropriate EDCA function. This is realized using credit-based schedulers (with two queues) as defined in IEEE 802.1Q [11]. This scheduler is configured so that frames from the primary queues are selected with a higher probability than frames from the alternate queues. The EDCA function remains unchanged for each AC and data transmission is organized using procedures defined in 802.11.

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[3] A proprietary mapping can be achieved with the Stream Classification Service, described in Section 3.3.

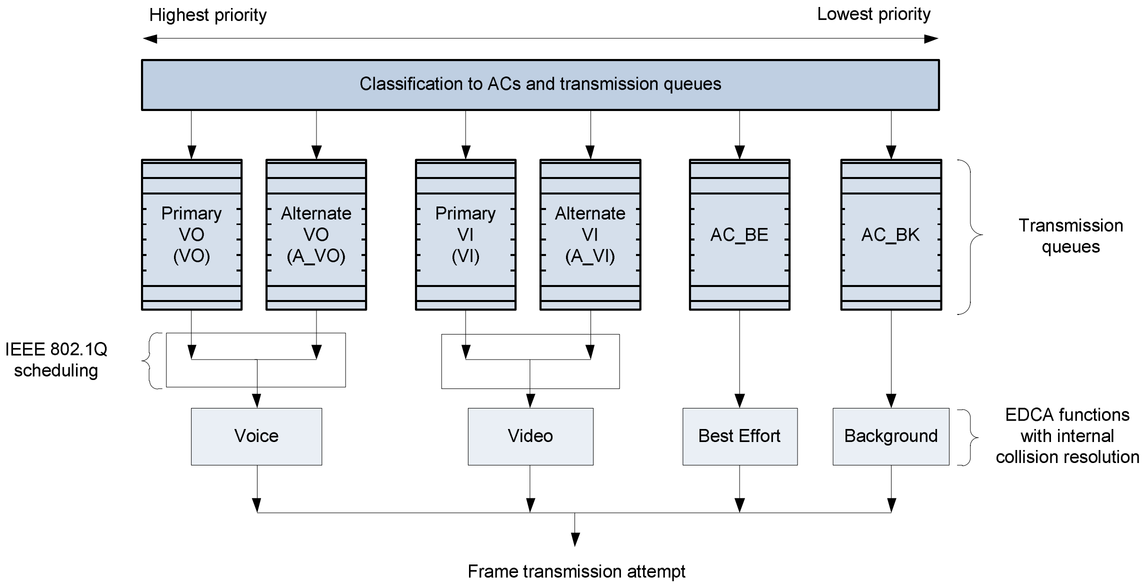

Figure 3 Intra-access category prioritization

The intra-AC traffic differentiation feature of 802.11aa can potentially, depending on the implementation, be applied to more elaborate use cases then simply differentiating between individual AV streams. For example, in the case of MPEG streaming, the particular types of video frames of the codec (I/P/B) can be assigned different priorities to ensure that the most important ones (I frames) are provided a higher QoS. Finally, the different layers of a video stream encoded with Scalable Video Coding (SVC) can be easily mapped onto the new transmission queues (e.g., using not only the VI and A_VI queues, but possibly also the BE/BK queues).

Intra-access category prioritization requires the use of the admission control mechanisms provided in the 802.11 standard (Section 2.1). Therefore, because of the necessary signaling, it is available only in the infrastructure and mesh network types. Furthermore, stations disseminate support for this feature using an additional signaling mechanism. This allows backward compatibility: a transmission with the use of the alternate queues will not be set up if the destination is a legacy station.

In order to demonstrate the intra-access category prioritization feature of 802.11aa consider a single AP simultaneously transmitting traffic in all six queues. All queues are saturated, channel conditions are ideal, and both credit-based schedulers are configured to achieve a probability of selecting a frame from the primary queue (p^{primary}) equal to 0.75 and 0.6 for VO and VI, respectively[4]. Given a fixed frame size of 1000 bytes, we can estimate the achieved throughput values based on an existing EDCA model [13] extended to support intra-access prioritization[5]. The results are presented in Figure 4.

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[4] The exact prioritization scheme, i.e., the configuration of the credit-based scheduling, is implementation-dependent.

[5] In brief, the probability of a successful transmission for the i-th AC (PS_i) from [13] was changed for VO and VI to accommodate the two new queues. It was changed to $p^{\text{primary}}PS_i$ and $(1-p^{\text{primary}})PS_i$ for the primary and alternate queues, respectively.

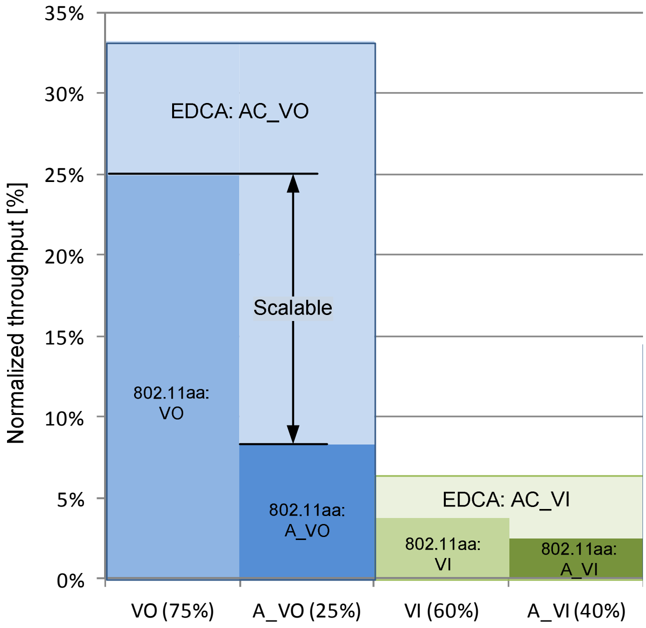

Figure 4 Example of intra-access category prioritization

Based on this example, the following conclusions can be derived. First, the prioritization levels achieved using 802.11aa are finer than using EDCA. In contrast to EDCA, 802.11aa allows splitting the throughput of VO into two distinct values (different VO queues are served with different priority). The same behavior is observed for VI. Second, inter-access category prioritization (EDCA) is not disrupted, i.e., VO is served with higher probability than VI, although it is possible that 802.11aa A_VO will have lower throughput than 802.11aa VI. Third, the relation of data selected from the primary queue to data selected from the alternate queue is scalable. It is dependent on the settings of the employed credit-based schedulers. The amendment does not define the parameter settings for the schedulers because they are dependent on the network configuration.

3.3 Stream Classification Service

When intra-access category prioritization is enabled, the Stream Classification Service (SCS) allows streams to be arbitrarily (i.e., not based on the 802.1D user priority) mapped to the primary and alternate queues. This is an optional service which may be realized using layer 2 and/or layer 3 classification. Additional information can also be provided to determine if the described traffic stream allows frame dropping. A designated Drop Eligibility Indicator (DEI) bit indicates that in this stream frames may be dropped. Therefore, by noticing that AV streams can tolerate a certain degree of packet loss [5], 802.11aa refrains from perfect reliability at the MAC layer. Such graceful degradation of AV streams is especially helpful if the capacity of the wireless channel is insufficient. However, determining at which stage frames should be dropped or if the capacity is insufficient is outside the scope of the amendment. Additionally, note that the combination of the two intra-AC queues and two settings of DEI allows four different priority types for both VO and VI.

Each SCS stream is identified by an SCSID which is used by a station to request the creation, modification, or deletion of an SCS stream. It is also used by an AP to identify the SCS stream in SCS responses. To start an SCS session, a station sends a request specifying the traffic class and priority for the new stream. The AP may accept or reject the requirements specified by the station. Once accepted and classified, the stream is assigned to an AC and tagged with a specific DEI.

An SCS session can be initialized by any non-AP station that supports it. This could be either the destination or the source station (Figure 5). Usually, the destination starts the session and requests the AV stream. A legacy station cannot initiate, modify, or terminate an SCS session, however, it can correctly receive SCS streams initiated by other non-AP stations. In the first case (Figure 5a), the destination node (an AV station) that supports SCS, can start the service by sending an SCS Request frame to the AP. After replying with an SCS Response frame, the AP should process all incoming unicast data frames that belong to the accepted AV stream based upon parameters provided in the SCS Request frame by the destination node. In the second case (Figure 5b), the source node (an AV server) can initiate an SCS session with the same procedure as described above even if the destination (a legacy station) does not support it.

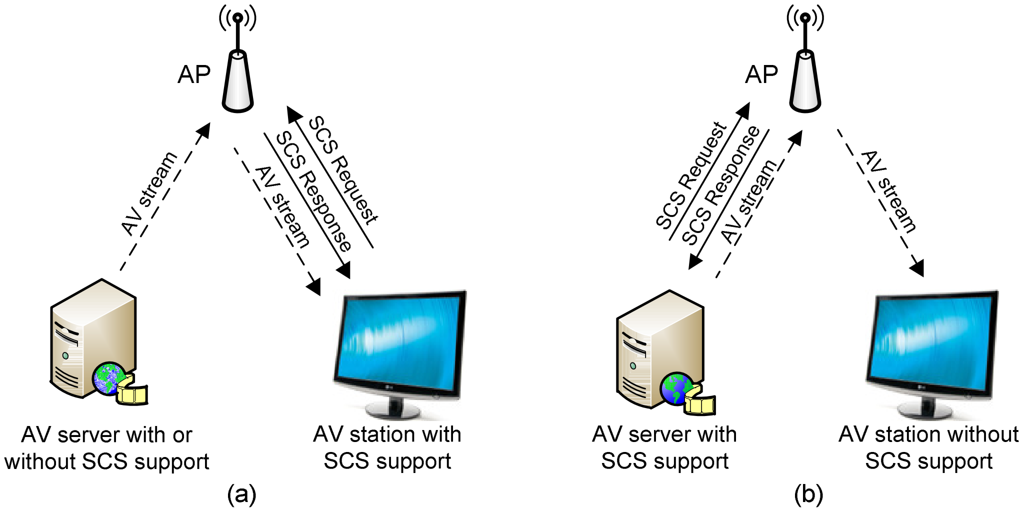

Figure 5 Initialization of SCS by (a) destination node or (b) source node

3.4 OBSS Management

OBSSs working on the same channel are becoming more and more common because of the wide diffusion of 802.11 networks and the limited availability of channels. Although the carrier sense mechanism in principle does not require any frequency planning (because it is based on a temporal division of BSSs operating on the same channel), it has been shown that severe performance impairments can occur due to the neighbor capture effect. This occurs when a BSS is between two BSSs which do not hear each other. In the presence of greedy traffic, the BSS in the middle can be prevented from accessing the channel indefinitely because it senses the medium permanently busy.

In order to limit the neighbor capture effect and extend admission control and scheduling decisions, a new mechanism called OBSS management has been proposed. The mechanism is based on two main components: i) a mechanism for quantifying the load and interference status of each BSS and signaling this information to the neighbor BSSs; ii) a mechanism for performing channel selection and cooperative resource sharing on the basis of such information. Load and interference information are distributed in a QLoad report, which can be sent by the AP upon request or optionally included in beacon frames. Load information elements conveyed in the beacons are ignored by legacy APs.

The load information refers to the QoS traffic admitted under EDCA and HCCA, and it is expressed in terms of the number of admitted VO and VI streams, and the medium occupancy fraction (minimum, mean, maximum value, and standard deviations) caused by such streams. Note that medium occupancy can be evaluated on the basis of the TSPECs of the admitted streams or on the basis of channel observations, while the occupancy intervals in HCCA can be separately accounted by a dedicated QLoad field (HCCA Peak). The standard distinguishes between admitted traffic (currently active VI and VO streams) and potential traffic load (EDCA and HCCA QoS load estimated by tracking the maximum values of the allocated traffic over a period of seven days).

The interference information is expressed by four different parameters: i) the number of OBSSs that can be heard by the target one; ii) the sum of the allocated traffic load signaled by all OBSSs (including the target one); iii) the EDCA Access Factor, i.e., the medium occupancy fraction due to the sum of the OBSSs potential traffic; iv) the HCCA Access Factor, i.e., the medium occupancy fraction due to the sum of the OBSSs HCCA Peak values.

On the basis of the QLoad report, different channel selection or sharing strategies can be employed. The goal is selecting a channel that is less loaded by QoS traffic. When the EDCA Access Factor evaluated for the selected channel is higher than 1 (i.e., there are over-allocations), it is recommended to use a sharing scheme to ensure that any already admitted or scheduled QoS streams are not impaired by the addition of streams from any OBSS. Two sharing schemes (proportional and on demand sharing) are suggested to avoid over-allocations. The basic idea is using the aggregated load information received by all the OBSSs for admitting or scheduling new streams (up to the potential traffic signaled in the Qload report).

Finally, OBSS management enables each AP to exchange HCCA scheduling information with the overlapping ones in order to cooperatively create HCCA schedules that do not collide. An AP can query its neighbors before deciding on the admission of a new stream. Alternatively, it can specify duration, service interval, and start times for each reserved stream in its beacon frame and track similar information provided by its neighbors.

In order to clarify the rationale of the parameters proposed for quantifying the load and the interference of multiple OBSSs we present an illustrative example. Figure 6 plots the throughput performance and the shared allocated load measured by an AP interfering with two different BSSs which do not hear each other. Specifically, we assume that the three different APs are deployed in a linear topology at regular distances, and that the carrier sense range and transmission range of each AP is slightly higher than such a distance (so that the first AP is not able to sense the transmissions of the third one). In each BSS, we consider an increasing number of stations. These stations are placed close to their corresponding APs so that a transmission by any station belonging to an exterior BSS is received by the middle AP. Each station transmits a multimedia CBR traffic stream to its AP, with uniform parameters (namely, with a rate r of 500 Kb/s, a payload P of 1500 bytes). As long as the number of streams increases and the BSS capacity is saturated, the performance of the BSS in the middle decreases to zero because of the neighbor capture effect. Such a situation can be avoided if we perform admission control based on the shared allocated medium time. The allocated medium time of each AP is represented by the channel busy time, measured in an observation interval of 1 s. Considering *n* streams in each BSS and the occupancy time $T=r/P\ (T_{data} + T_{ack})$ of a single traffic stream, each AP computes the shared allocated medium time as the maximum between its local computation (i.e., the sum of the allocated times signaled by the neighbor plus its own allocated time) and the same parameter signaled by the neighbor APs. Since the AP in the middle will signal a shared allocated time of *3n T*, all the APs will consider such an interference indication (plotted in the right y axis of the figure). In 802.11aa new traffic streams are not admitted when this parameter is higher than 1 s (i.e., when the number of already admitted streams is equal to or greater than five in the considered scenario). Therefore, overloading conditions and subsequent unfair resource reparations among the BSSs can be prevented.

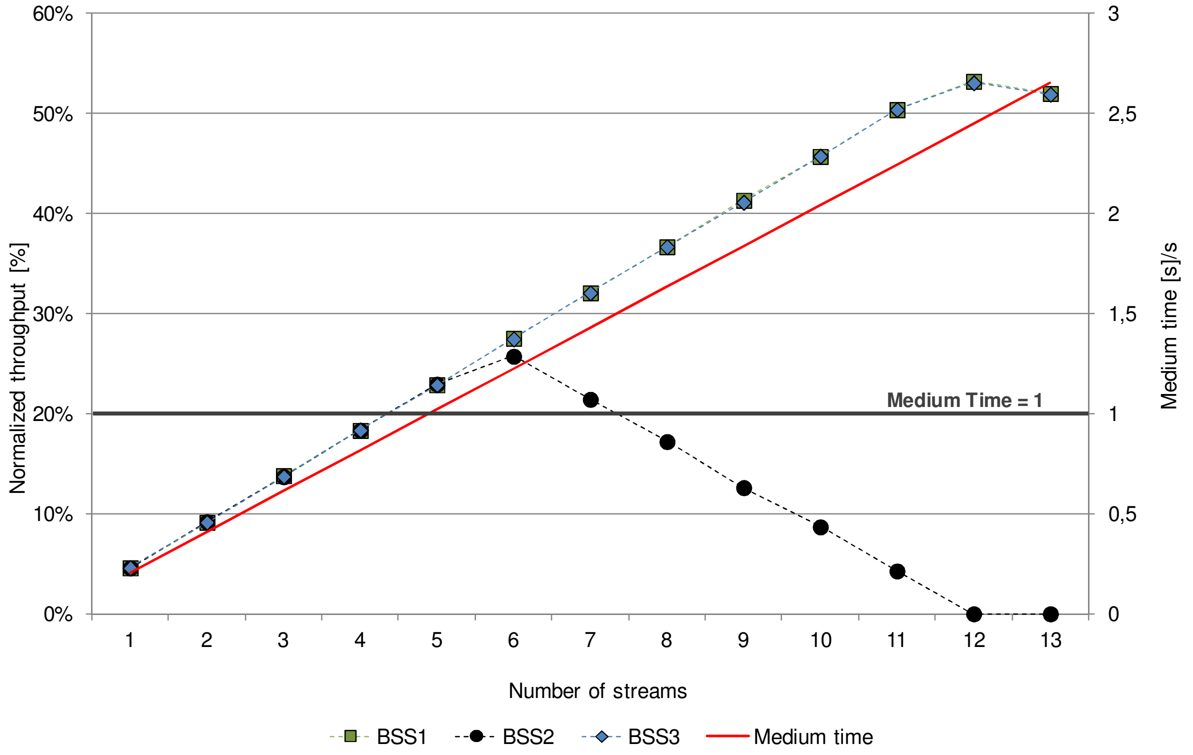

Figure 6 Throughput degradation in an OBSS scenario

3.5 Interworking with IEEE 802.1Q SRP

The Stream Reservation Protocol (SRP) is a signaling protocol defined in IEEE 802.1Q to provide end-to-end QoS guarantees by reserving network resources for specific traffic streams in bridged local area networks. Therefore, it can be considered equal in functionality to the Resource Reservation Protocol (RSVP) which operates in routed local area networks. SRP is very important because other IEEE 802 standards do not define procedures for such end-to-end reservations. 802.11aa introduces support for SRP by integrating it with admission control (specifically, with the TSPEC frames). This approach allows for end-to-end SRP reservations when one or more 802.11 links are along the path from the 802.1Q talker (data stream producer) to the 802.1Q listener (data stream consumer). In order for the SRP reservation to succeed, this feature has to be supported by the originating station, the AP to which it is connected, as well as the end-point of the reservation.

4 IEEE 802.11ae

Since 1999, the IEEE 802.11 standard has had 19 amendments. These amendments have significantly increased the number of management frame categories: from 11 indivisible types to 14 types with the action frame type having 18 categories, each with its own set of up to 28 sub-categories of frames. These management frames, though often of limited size, can impede the performance of voice applications if they are sent frequently and with the highest priority as in 802.11. The solution to this problem has been provided in the 802.11ae amendment. This concise document defines: (a) a mechanism for the flexible prioritization of management frames and (b) a signaling protocol for the exchange of frame prioritization policies.

The prioritization mechanism is called the QoS management frame (QMF) service. At its core is a QMF policy which provides a mapping between the management frame types/subtypes and the EDCA ACs[6]. This means that all management frames are sent in an AC as defined by the current QMF policy (Figure 7). Therefore, the QMF policy can be considered analogous to the mapping presented in Table 2.

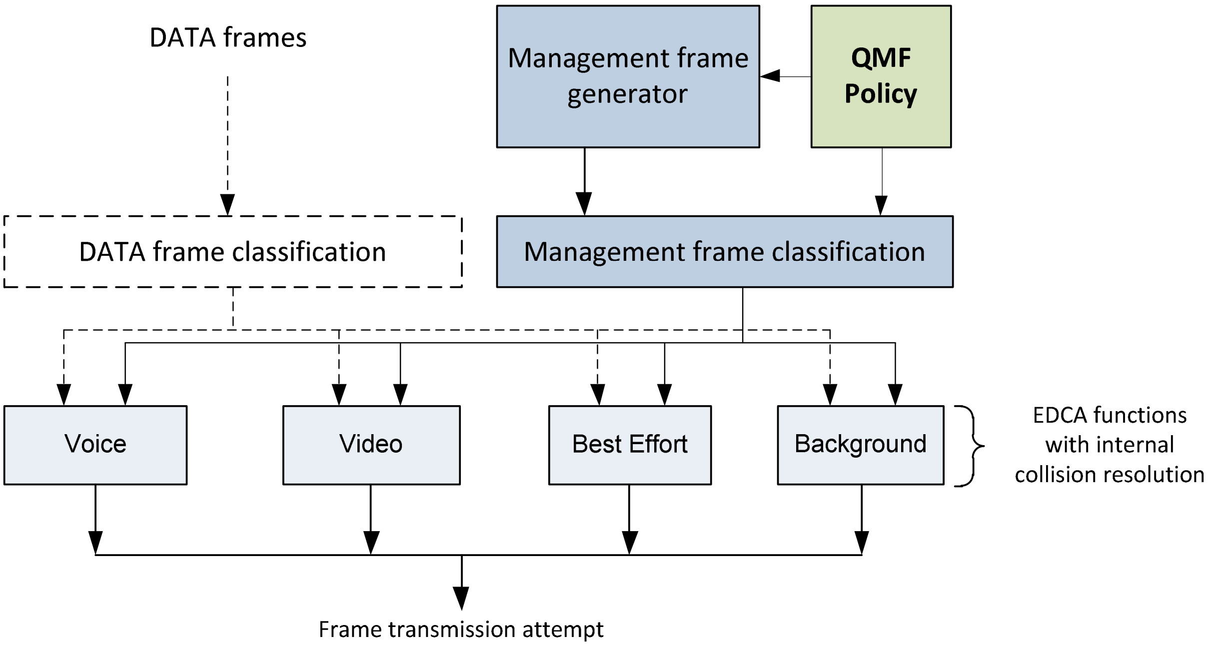

Figure 7 Operation of QMF

The amendment defines a default QMF policy (Table 3). However, in general the QMF policies are flexible, i.e., they can be established and changed using a signaling protocol defined in 802.11ae. This flexibility allows the QMF service to be adapted to vendor application requirements. The operation of the signaling protocol depends on the network type: infrastructure or mesh[7]. In the former, the AP defines the QMF policy for the whole BSS. In the latter, a mesh station defines the QMF policy with another mesh station on a per-link basis. The QMF policy can be disseminated using either existing frames (e.g., beacons) or new, dedicated frames (Table 3). Additional signaling mechanisms allow stations and frames to be identified as QMF stations (i.e., stations supporting this service) and QMFs (i.e., being sent according to a QMF policy), respectively. This allows backward compatibility: QMF

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[6] The alternate VO/VI queues defined by 802.11aa cannot be used to send management frames.

[7] The amendment does not allow QMF to be used in independent BSS (i.e., ad hoc) networks.

stations use VO to transmit management frames to non-QMF stations and group-addressed QMFs are not sent if there are non-QMF stations present in the BSS. Further backward compatibility is ensured if there are non-QoS stations in the network. In this case, all management frames are sent using BE.

Table 3 Default QMF policy (omitted frames are assigned to BE) and policy dissemination frames (emphasized)

Type of Frame	Frame Description	QMF Access Category	Dissemination of QMF Policies	
			Infrastructure BSS	Mesh BSS
(Re)Association Request/Response	**Handover between APs**	**VO**	**Yes (in responses)**	**No**
Probe Request (individually addressed)	Scanning initialization (unicast)	VO	No	No
Probe Response	**Scanning result**	**BE**	**Yes**	**No**
Beacon, ATIM, Disassociation, Authentication, Deauthentication	**Network maintenance**	**VO**	**Yes (beacon)**	**No**
Channel switch announcement	Initialization of channel switching	VO	No	No
Extended channel switch announcement	Initialization of extended channel switching	VO	No	No
QoS frames	QoS signaling (e.g., TSPEC exchange)	VO	No	No
Measurement pilot	Basic scanning information	VO	No	No
Tunneled Direct-Link Setup Discovery Response	Part of direct-link setup	VO	No	No
Fast BSS Transition	Pre-handover setup to speed up the handover process	VO	No	No
High Throughput frames	Support for data rates greater than 100 Mb/s	VO	No	No
Security Association Query frames	Procedure for robust management frame protection	VO	No	No
QMF Policy and QMF Change Policy	**Dedicated frames for the dissemination of QMF policies**	**BE**	**Yes**	**Yes**
Hybrid Wireless Mesh Protocol Mesh Path Selection	Path selection in mesh BSS	VO	No	No
Congestion Control	Congestion information dissemination in mesh BSS	VO	No	No
Self Protected frames	Management of security associations	VI	No	No
Deenablement of Dynamic Station Enablement	Related to the operation in the 3650 to 3700 MHz band in the US	VO	No	No

5 Conclusions and Future Work

The IEEE 802.11 standard has been continuously evolving since its first release in 1999. In this tutorial we have discussed two recently published amendments to the standard which focus on increasing QoS by providing several new features. Some of them extend already existing mechanisms (inter-access category prioritization, prioritization of management frames, 802.1 AVB, reliable multicast and broadcast) while others introduce mechanisms previously not considered in 802.11 (stream classification service, OBSS management, graceful degradation of AV streams). For each of the new features, we have explained the motivation for their introduction, described their design principles, provided examples of usage, and discussed compatibility issues.

Amendments to 802.11, such as those described in this tutorial, always introduce new challenges. A recent example of this problem is related to 802.11s. It has been shown in [7] that transmissions in MCCAOPs are not fully protected from interference (e.g., caused by acknowledgement frames from hidden nodes). Solutions which can protect reservations from interference and guarantee reliable transmission within MCCAOPs, such as those presented in [7], are required. Table 4 provides a list of similar challenges related to 802.11aa and 802.11ae. This table can be considered as a guideline for researchers working in the area of Wi-Fi networks. It can be expected that in the nearest future more challenges will be identified and extensively researched. Additionally, we can expect the emergence of solutions which will allow the dynamic adaptation of 802.11aa and 802.11ae parameters, similarly to those proposed for EDCA [15].

Table 4 Open research areas related to the new IEEE 802.11 QoS amendments

New 802.11 QoS Functionality	Open Research Area	Comments
Multicast	Choice of delivery method for multimedia traffic	The choice between broadcast, directed multicast, and the two GCR methods depends on such factors as number of recipients, their PER, and the QoS requirements of a particular stream.
GCR Block Ack	Choice of groupcast recipients for providing block acknowledgements	This choice can be based on such QoS metrics as delay, throughput, and PER. A comparison of several schemes can be found in [8].
Intra-AC traffic prioritization	Mapping of streams to either primary and alternate queues	A performance analysis of the newly introduced transmission queues is required.
Intra-AC traffic prioritization	Mapping of individual frames to multiple queues	It remains to be analyzed how given multimedia applications (e.g., using SVC) might benefit from the use of multiple queues.
Intra-AC traffic prioritization	Scheduling between primary and alternate queues	The selection of parameters for the credit-based schedulers is left open.
SCS	Graceful degradation of AV streams	It is necessary to determine which frames should be dropped if the existing radio channel capacity is insufficient.
OBSS management	Algorithms for channel selection and channel sharing	The 802.11aa amendment outlines recommended algorithms but additional factors (e.g., interference from non-802.11 systems) may also need to be included.
OBSS management	Security of inter-BSS data exchange	Frames exchanged by OBSSs may not be authenticated or encrypted. Therefore, additional information (e.g., history of collaboration) may be required as verification.
OBSS management	Estimation of non-QoS traffic	Since QLoad reports contain information only on the traffic load generated by admitted VO and VI streams, it might be beneficial to additionally consider traffic load from non-QoS sources.
QMF	Optimum QMF policy	The optimization of custom QMF policies according to network deployment, traffic load, etc. is left open.

The verification of the new functionalities proposed both by IEEE and researchers worldwide can be greatly facilitated by open MAC architectures. Such an architecture is currently being designed within the FLexible Architecture for Virtualizable wireless future Internet Access (FLAVIA) project [14]. With FLAVIA it will be possible to easily check which new solutions, protocol extensions, and optimizations are best suited to specific environments and services without the need of standardizing them first. In particular, in view of QoS, it will enable avoiding suboptimal multimedia performance.

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