UNIVERSITY CARLOS III OF MADRID

Department of Telematics Engineering

Master of Science Thesis

Performance Evaluation of IEEE 802.11aa MAC Enhancements for Robust Audio Video Streaming

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Abstract

Video traffic is foreseen to account for the majority of the Internet traffic in the near future. While the demand of video transmission keeps growing, the vast majority of wireless equipment deployed in the home environment, based on IEEE 802.11, does not support robust multicast transmission that video applications require. In order to cope with the increasing demand of multimedia traffic, the IEEE 802.11aa Task Group is standardizing new mechanisms that allow the efficient transmission of unicast/multicast multimedia flows in Wireless LAN. In this thesis, we provide analytical models for the throughput of new mechanisms proposed by the Task Group and we validate them through simulation. We also study the reliability via simulation, providing insight into new methods included in the standard to handle group addressed frames.

Table of Contents

List of Figures

Acronyms

AC	Access Category
ACK	Acknowledgement
AIFS	Arbitration IFS
AP	Access Point
BSS	Basic Service Set
BT	Backoff Time
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CW	Contention Window
DCF	Distributed Coordination Function
DEI	Drop Eligibility Indicator
DIFS	DCF IFS
DMS	Directed Multicast Service
EDCA	Enhanced Distributed Channel Access
FCS	Frame Check Sequence
GCR	Groupcast with Retries
GCR-SP	GCR Service Period
IFS	Interframe Space
MAC	Medium Access Control
MSC	Message Sequence Chart
OBSS	Overlapping BSS
PHY	Physical Layer
PLCP	Physical Layer Convergence Protocol
QoS	Quality of Service
RTS/CTS	Request To Send / Clear To Send
SCS	Stream Classification Service
SIFS	Short IFS
STA	Station
TC	Traffic Class
TS	Traffic Stream
ToS	Type of Service
TXOP	Transmission Opportunity
UR	Unsolicited Retry
WLAN	Wireless Local Area Network

Chapter 1

Introduction

The IEEE 802.11 standard for Wireless LAN (WLAN) [3] has become one of the most common technologies to provide broadband connectivity to the Internet. The widespread deployment of high-rate access points (APs), with modulation schema reaching up to 150 Mbps as defined by the amendment 802.11n [4] is enabling the introduction of applications with relatively large bandwidth demands, like e.g., YouTube, Skype videoconferencing or VideoLAN video-streaming.

The original 802.11 standard was poorly suited for the efficient support of multimedia flows, and in particular video streams, because of several reasons: i) the originally supported physical transmission rates (1 and 2 Mbps) imposed a severe bottleneck on the maximum achievable rate, regardless of the efficiency of the MAC protocol; ii) only "best-effort" service was supported, thus preventing any sort of traffic differentiation that could improve the performance of multimedia applications, which as compared to data can relax their reliability requirements below 100 % to improve performance; iii) multicast transmissions were very inefficient and unreliable (as widely reported in various works, see e.g. [11]), which eventually prevented its use on WLANs, as there is no proper support for video streaming to various receivers.

The subsequents amendments to the 802.11 standard have lessen the first two limitations. Indeed, as already mentioned, the introduction of PHY-amendments have boosted the maximum achievable rates, starting with the 802.11b [1] that increased the maximum rate up to 11 Mbps, continuing with the 802.11a and 802.11g amendments that reach up to 54 Mbps, and finally with the 802.11n [4] which specifies modulation rates up to 600 Mbps when using four spatial streams of 150 Mbps. On the other hand, the 802.11e amendment [2] has introduced traffic differentiation via the setting of the contention parameters, thus enabling both the ability to prioritize one type of traffic over other type [7] and a more efficient operation of WLANs by proper tuning of the MAC parameters [15]. The remaining challenge, therefore, is to efficiently support multicast over 802.11 WLANs.

The IEEE 802.11aa Task Group is addressing the multicast limitation, with the definition of the mechanisms to support "Robust streaming of Audio Video Transport Streams". Its focus is therefore to extend the base 802.11 standard with those mechanisms that improve performance of multimedia streaming over WLAN. In particular, as we will describe in Section 2 and validate via models and simulations in Sections 3 and 4, the new mechanisms target at significantly improving both the effectiveness and efficiency of multicast, allowing for a fine-grained control of the type of service provided to video traffic.

In this thesis, we present a model and simulation-based evaluation of the mechanisms defined in the current version of the standard, in order to assess their performance in a mixed scenario with video streams and data traffic. We quantify the throughput and the reliability that each of the considered mechanisms provides to a video stream for different number of receivers as well as the efficiency in terms of the bandwidth that is left for data users. Our results show that: i) indeed the new defined mechanisms substantially enrich the set of services than can be offered to multimedia streams in 802.11 WLANs; ii) there is no clear "winner" as each of them offers different trade-offs between efficiency, reliability and complexity, depending on the considered scenario.

The rest of the thesis is organized as follows. In Section 2, we provide a short summary of the different mechanisms that can be used to transport multimedia traffic over 802.11 WLANs, considering both the existing mechanisms as defined in the current standard and the new mechanisms being discussed within TGaa. In Section 3, we present the analytical models developed to study the throughput of the new multicast mechanisms in a mixed WLAN scenario under saturation conditions. In Section 4 we validate the models for the throughput via simulation and we study the reliability of each mechanism also via simulation. Finally, in Section 5 we summarize the main results and we describe the future lines of research.

Chapter 2

Streaming on IEEE 802.11 WLANs

2.1 Multimedia Transmission over Legacy IEEE 802.11 WLANs

As described in the previous section, IEEE 802.11 WLANs did not support efficient delivery of multimedia streams. Subsequent amendments have triggered their widely deployment, due to its reduced price and high bandwidth, becoming the "technology of choice" to connect different devices in, e.g., residential deployments. Although the IEEE 802.11n amendment provides a large increase in terms of achievable bandwidth, the new demands due to the arrival of high definition video impose a several burden on the current MAC schema, in particular for the delivery of multicast traffic. In this section we summarize the main MAC mechanisms that can be used to support multimedia services over 802.11 WLANs, considering both the current standard and the new 802.11aa amendment.

Audio and video streaming over IEEE 802.11 can be performed using either multicast or unicast transmission. The choice of transmitting the audio/video content on multicast or unicast does not depend only on the number of receivers of the traffic, since the multicast transmission in the base IEEE 802.11 standard has some specificities that must be considered.

2.1.1 Multicast Service

IEEE 802.11 defines multicast as the frames (data frames) with a multicast address as the Destination Address, and it defines a specific mechanism to transmit them. Specifically, only the basic access procedure shall be used. This means that regardless of the length of the frame, no RTS/CTS exchange shall be used. In addition, no ACK shall be transmitted by any of the recipients of the frame. The lack of MAC-level recovery on multicast frames has as result a reduced reliability of this kind of traffic, due to the increased probability of lost frames from interference or collisions. In addition, all multicast addresses must be transmitted at one of the rates included in the Basic Rate Set. This set is defined at the Access Point (AP) and includes the minimum set of rates that a station must support in order to join the BSS. Although it is not a requirement, usually the Basic Rate Set includes only rates with lower order modulations, so the transmission of multicast frames is performed at a reduced speed, hence decreasing the overall performance of the BSS.

2.1.2 Unicast Service

The second choice for transmitting audio/video frames is the use of unicast traffic. Unlike multicast, unicast traffic can be transmitted at any rate and it is acknowledged, so its reliability is higher than standard multicast traffic. The counterpart is that the bandwidth and delay required to transmit the same flow to multiple receivers grow with the number of stations receiving it. Hence, it is only feasible for low bit rate flows and a reduced number of receiving stations.

2.1.3 Prioritization

With the latest additions regarding QoS to the standard, unicast and multicast traffic can be differentiated and prioritized, so regardless of its transmission on unicast or multicast, the network can be configured so multimedia flows can receive some advantage while accessing the medium compared with the rest of traffic. Although this is clearly an advantage, one of the problems already identified with this approach is the definition of only one queue for video traffic. Current codecs do not generate equal frames, being some of them more important than others. A better solution would be to allow traffic differentiation within the video flow, which is a mechanism adopted in the new extensions that we address in the next section.

2.2 MAC Enhancements for Robust Audio Video Streaming: IEEE 802.11aa

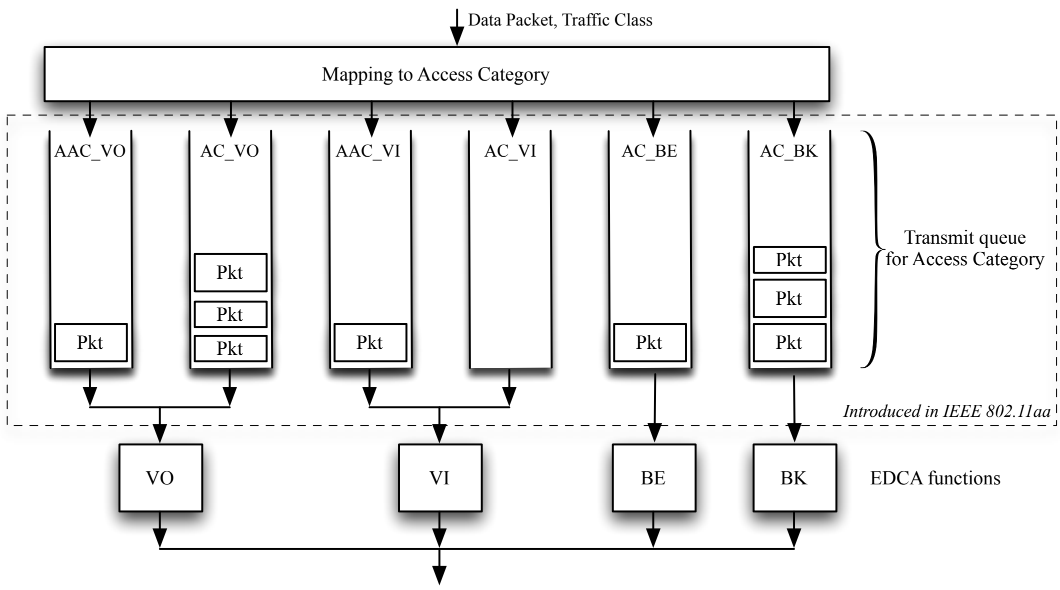

Figure 2.1: Stream Classification Service over the standard EDCA mechanism.

As explained in the previous section, the availability of mechanisms to perform video streaming over 802.11 WLANs is rather limited. The upcoming IEEE 802.11aa amendment is being designed to specifically address the challenge of multimedia transmission, implementing a set of new functionalities over the base specification. In this section, we describe the main extensions to the IEEE 802.11 standard as defined in the 802.11aa Draft 6.0 [5]. The objective of these extensions is to efficiently improve the reliability of audio and video streaming, while maintaining and even improving the service as perceived by the other streams. The amendment also specifies related functionality (e.g., OBSS management, interworking with IEEE 802.1AVB) but we only consider the case of a single WLAN. Following this, we consider the following two mechanisms:

- Stream Classification Service (SCS).
- Groupcast with Retries (GCR) service.

In the following we present these new functionalities.

2.2.1 Stream Classification Service

This service is built over the EDCA access mechanism which is based on different access categories (ACs) and supports traffic differentiation by means of priorities between queues and heterogeneous configuration of the contention parameters (namely $AIFS$, CW and $TXOP$). The *SCS*, along with the intra-Access Category (AC) Traffic Stream (TS) prioritization, enables classification using layer 2 and/or layer 3 signaling and increases the granularity of the service differentiation already provided by the EDCA mechanism.

More specifically, as illustrated in Fig. 2.1, this service introduces two additional queues within the existing EDCA access categories: one additional queue for audio (AAC_VO) and another one for video (AAC_VI), in order to support prioritization within the video flows. Furthermore, in addition to this intra AC prioritization, packets are tagged with their drop eligibility indicator (DEI), which defines a different maximum number of (short and long) retries.

With this availability of additional access categories and the drop eligibility bit, graceful degradation of video quality is supported in case of bandwidth shortage. However, it should be noted that the SCS does not alter the standard MAC behavior, as it builds on the existing EDCA mechanism. Therefore, it inherits the same limitations of the EDCA mechanism with respect to video streaming, being either i) extremely unreliable, in case of multicast, or ii) extremely inefficient, in case of unicast transmissions to a moderate number of receivers (as we will see in the next section).

2.2.2 Groupcast with Retries Service

Two of the main weaknesses of the use of multicast in existing 802.11 WLANs, as described in Section 2.1.1 are: i) the poor reliability of the service, since multicast frames are not acknowledged, and ii) the high inefficiency due to the use of a low modulation coding scheme, as it uses the largest rate available in the Basic Rate Set. In order to overcome these limitations, the IEEE 802.11aa draft standard proposes several new mechanisms to improve the performance and efficiency of the delivery of frames addressed to a group of stations. This way, in addition to the *legacy* multicast service (that we denote as "No-Ack/No-Retry"

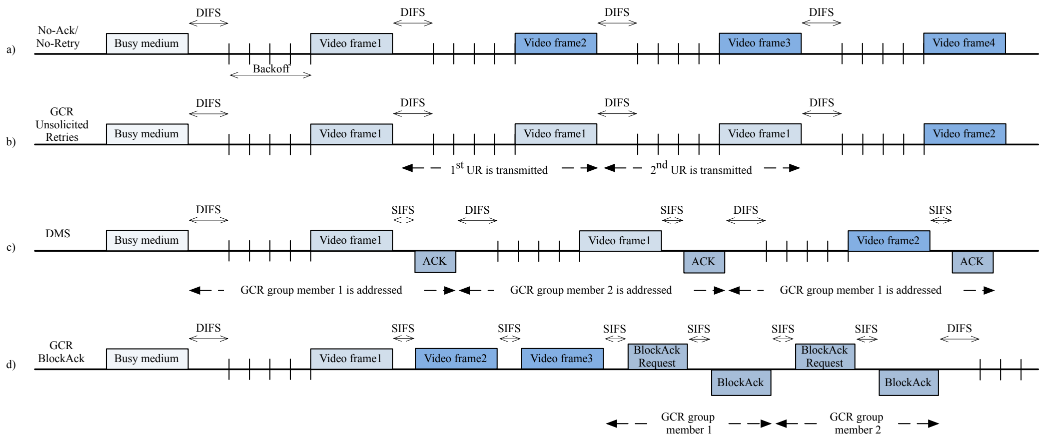

Figure 2.2: Available mechanisms with the Groupcast with Retries Service (GCR).

in Fig. 2.2), the IEEE 802.11aa specifies the following new mechanisms (illustrated in the same Figure):

- GCR Unsolicited Retry. This delivery method *preemptively* retransmits a frame one or more times (up to a certain lifetime limit), to increase the delivery probability at the STAs (see Fig. 2.2b). The retransmission of these frames is implementation-dependent. This way, the mechanism aims at improving the reliability of the legacy multicast without introducing the associated overhead of an acknowledgement mechanism.

- Directed Multicast Service (DMS). This mechanism basically consists on the conversion multicast to unicast (as illustrated in Fig. 2.2c for two groupcast members). This way, those frames transmitted to a multicast address are individually transmitted to each of the associated STAs that joined the multicast group. The individually addressed frames will therefore be retransmitted until an ACK is received at the AP, or the retransmission count limit is exceeded (in which case the frame is discarded). It is clear to see that, although this mechanism provides very high reliability, has large scalability constrains as the required throughput increase with the number of group members. Note that this mechanism was first introduced in IEEE 802.11v [6] and extended to target with groupcast addressed frames.

- GCR Block Ack. This mechanism extends the Block Ack mechanism already defined in the current version of the standard to account for group addressed frames. While with the previous mechanism the sender transmitted a burst of data frames and then explicitly requested an ACK to the receiving station, in this case is the AP or *originator* the one that, after transmitting no more than GCR buffer size frames to the GCR group address, sends a *BlockAckRequest* frame to one of the destination STAs or *recipients*. After receiving the *BlockAck* from this STA, the AP may send another *BlockAckRequest* to another STA belonging to the same group of receiving station (the mechanism is also illustrated in Fig. 2.2d).
  There are two possible Block Ack mechanisms:

- Immediate Block Ack
- Delayed Block Ack

The recipient of a BlockAckRequest replies immediately (after a SIFS time) with a BlockAck frame. In contrast, in the Delayed Block Ack, after receiving a BlockAck-Request the recipient starts a backoff process before sending the BlockAck frame. With the Delayed Block Ack, both the BlockAckRequest and the BlockAck frames are acknowledged with an ACK frame. In the following we describe the operation of each of these two mechanisms with further detail, illustrating it with Message Sequence Charts (MSCs).
Figure 2.3 shows a frame exchange example in which the AP transmits to the GCR group formed by two video stations a burst of N video frames using the GCR Immediate Block Ack mechanism. N' out of the N frames will collide and will be retransmitted. In case of the control frames, BlockAckReq frames will be retransmitted after a DIFS if no BlockAck for the corresponding GCR group member is received after a SIFS interval. A backoff will occur only after the BlockAckReq and BlockAck frame exchange always with the minimum contention window CW_{min} and a maximum backoff stage $m = 0$. Figure 2.4 shows the MSC for the same previous scenario but using GCR Delayed Block Ack policy. We can see that backoff is performed after a burst transmission with CW_{min} and $m = 0$, and after every BlockAckReq-Ack or BlockAck-Ack with CW_{min} and $m \neq 0$.

Note that the draft proposes these mechanisms but no setting of the parameters or guidelines are provided in order to pick the most efficient one for a given scenario. This is the main motivation of this thesis which we tackle in the next section. We will provide a performance assessment of each of the mechanisms from the GCR service in order to properly understand their benefits and limitations.

2.3 Related Work

The analysis presented in this thesis is more related to the modeling of the mechanisms described in the IEEE 802.11aa Draft than to the video transmission over WLAN. More specifically, we have based our research in the analytical model for DCF presented in [9] as well as in the analysis of EDCA in [7] which adds QoS capabilities that allow the prioritization between different types of traffic, like e.g., data and video. Additionally, due to the poor performance of legacy IEEE 802.11 multicast, other mechanisms have been proposed in the literature to improve it. In [12] a leader-based ACK mechanism is proposed in which the acknowledgments are performed only by the receiver station with the weakest link. And in [8] a network coding approach is proposed to improve multicast error control on WLAN. The main drawback of these proposals is that they require changes in the physical layer of the current MAC making difficult its deployment as well as the coexistence with legacy IEEE 802.11.

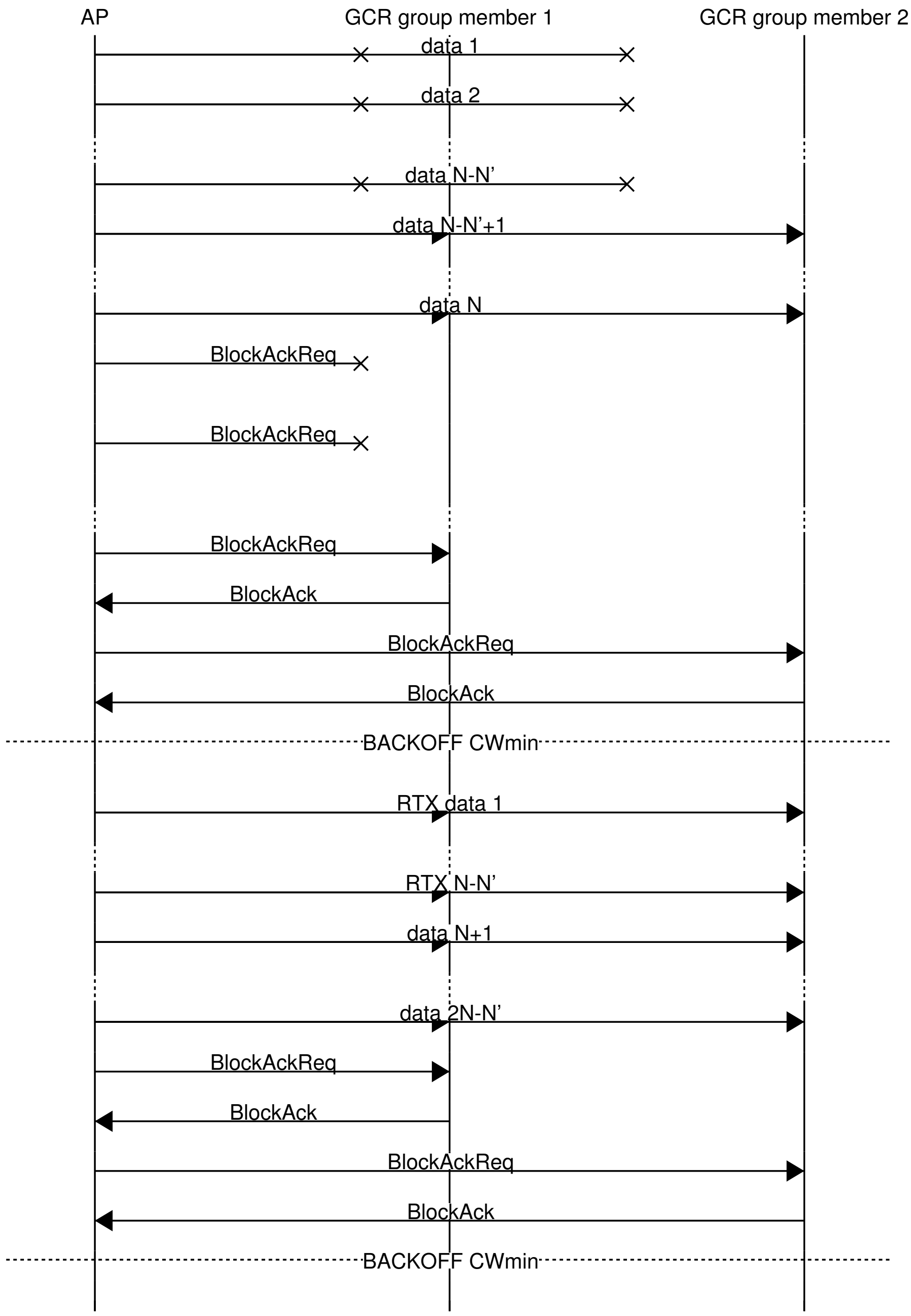

Figure 2.3: Immediate Block Ack policy with video and control frame recovery

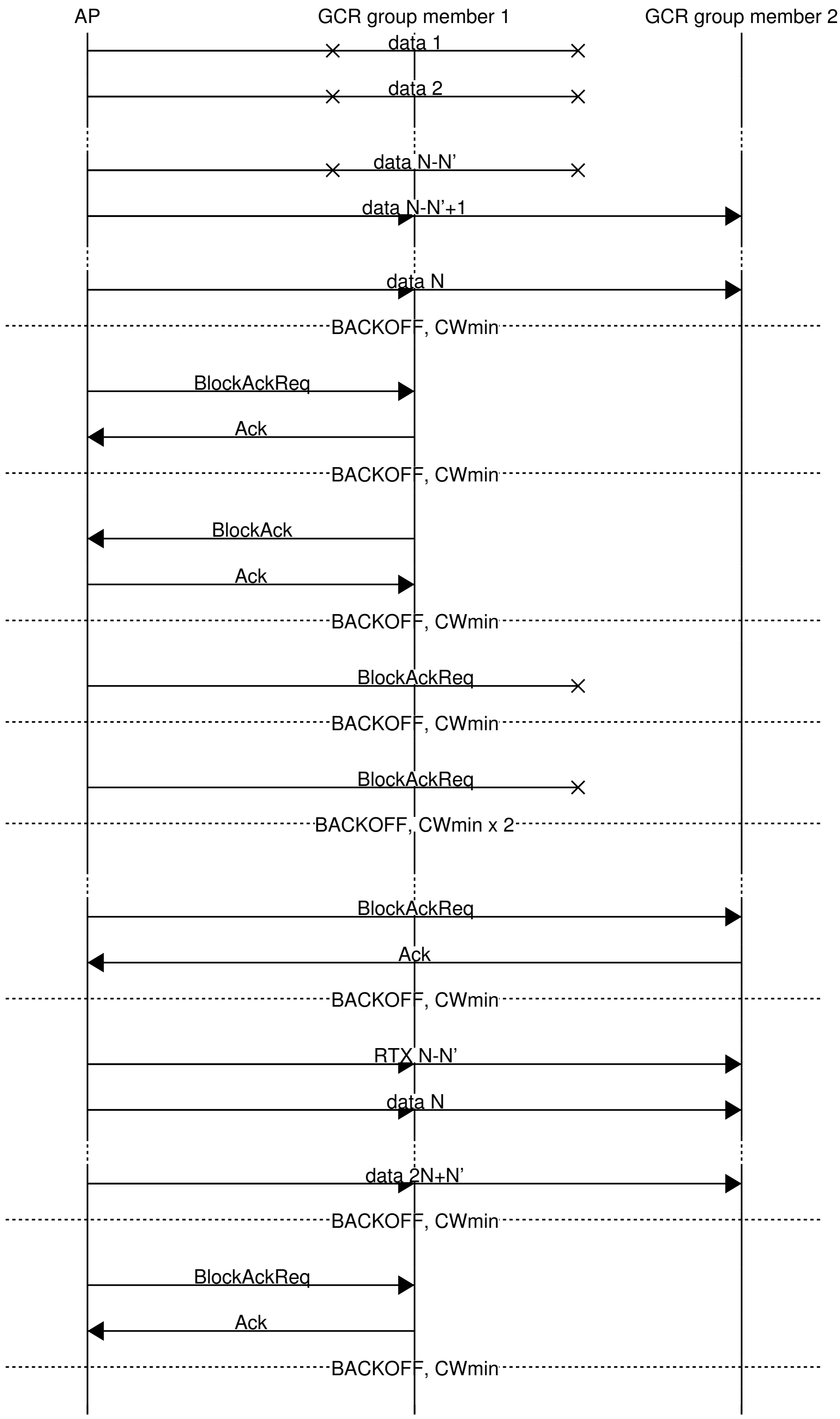

Figure 2.4: Delayed Block Ack policy

Chapter 3

Performance Analysis

In this section we analyse the throughput of the legacy No-Ack/No-Retry and the new multicast mechanisms under specification in the IEEE 802.11aa Draft. Our analysis builds on the widely used work of [9] and assumes that the reader is familiarized with it.

3.1 Scenario and Assumptions

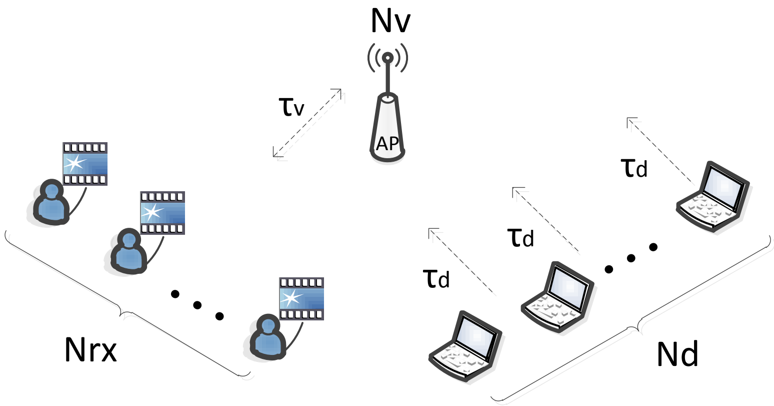

Figure 3.1: Considered scenario

We describe the assumptions and the scenario shown in Figure 3.1 upon we will rely for our analysis:

- We consider two types of traffic:
  - Video traffic which is generated in saturation by N_v video stations using one of the multicast mechanisms that are the object of analysis. It is addressed towards a variable number of video receivers N_{rx}. In Figure 3.1, N_v is particularized in a single AP.
  - Data traffic which is generated towards the AP by a variable number of stations N_d in saturation conditions and using the DCF mode.

- N_{rx} are the video receiver stations that form the GCR group and are the recipients of the multicast traffic sent by the AP.
- We have ideal channel conditions, i.e., an error-free channel in which the only sources of packet losses are collisions between stations, i.e., two or more stations access the channel simultaneously.
- We differentiate between video collisions – video frames collide with other video or data frames – and data collisions – data frames collide with other data frames.
- The collision probabilities for video p_{c_v} and data p_{c_d} are independent of the backoff stage but they are functions of the transmission probabilities for video τ_v and data τ_d.

3.2 No-Ack/No-Retry Model

3.2.1 Throughput analysis

In this section we compute the throughput of data stations r_d and video stations r_v when video stations transmit using No-Ack/No-Retry multicast mode. Those throughputs are function of τ_d and τ_v which are the probabilities that data stations and video stations transmit in a randomly chosen slot time, as well as of N_d and N_v and can be computed as:

$$r_d = \frac{P_{s_d} L_d}{T_{slot}} \tag{3.1}$$

$$r_v = \frac{P_{s_v} L_v}{T_{slot}} \tag{3.2}$$

where P_{s_d} and P_{s_v} are the probabilities that a random slot time contains a succesful data or video transmission respectively, L_d and L_v are the length of the data and video frames, and T_{slot} is the total slot time duration which is computed as:

$$T_{slot} = P_{s_d} T_{s_d} + P_{c_d} T_{c_d} + P_{s_v} T_{s_v} + P_{c_v} T_{c_v} + P_e T_e \tag{3.3}$$

P_{c_d}, P_{c_v} and P_e are the probabilities that a random slot time contains a data collision, a video collision or an empty slot respectively and, T_{c_d}, T_{c_v} and T_e the slot time duration in each case. Using No-Ack/No-Retry the slot times can be computed as:

$$T_{s_d} = T_{PLCP} + \frac{H}{R_d} + \frac{L_d}{R_d} + SIFS + T_{PLCP} + \frac{ACK}{R_c} + DIFS \tag{3.4}$$

$$T_{c_d} = T_{PLCP} + \frac{H}{R_d} + \frac{L_d}{R_d} + DIFS \tag{3.5}$$

$$T_{s_v} = T_{c_v} = T_{PLCP} + \frac{H}{R_v} + \frac{L_v}{R_v} + DIFS \tag{3.6}$$

where T_{PLCP} is the Physical Layer Convergence Protocol (PLCP) preamble, H is the MAC header plus the Frame Check Sequence (FCS) length, ACK is the length of the Ack frame and, R_d, R_v and R_c are the channel bit rate for data, video and control frames respectively. We note that No-Ack/No-Retry multicast uses for R_v one of the Basic Service Set.

We denote p_{c_v} as the probability that a video transmission attempt collides [1] . Therefore, the probability of not colliding occurs when none of the N_d data stations nor the other $N_v - 1$ video stations are transmitting and can be expressed as:

$$(1 - p_{c_v}) = (1 - \tau_d)^{N_d} (1 - \tau_v)^{N_v - 1} \tag{3.7}$$

With the above, the probability p_{s_v} that a video transmission attempt is successful can be computed as:

$$p_{s_v} = \tau_v \ (1 - p_{c_v}) = \tau_v \ (1 - \tau_d)^{N_d} (1 - \tau_v)^{N_v - 1} \tag{3.8}$$

For all the N_v video stations, the probability that a random slot contains a successful video transmission is:

$$P_{s_v} = N_v \, p_{s_v} = N_v \, \tau_v \ (1 - \tau_d)^{N_d} (1 - \tau_v)^{N_v - 1} \tag{3.9}$$

Similarly, if p_{c_d} is the probabililty that a data transmission attempt collides then the probability of not colliding occurs when none of the other N_{d-1} data stations nor the N_v video stations are transmitting:

$$(1 - p_{c_d}) = (1 - \tau_d)^{N_d - 1} (1 - \tau_v)^{N_v} \tag{3.10}$$

and the probability p_{s_d} that a data transmission attempt is successful can be computed as:

$$p_{s_d} = \tau_d \ (1 - p_{c_d}) = \tau_d \ (1 - \tau_d)^{N_d - 1} (1 - \tau_v)^{N_v} \tag{3.11}$$

For all the N_d data stations, the probability that a random slot contains a successful data transmission is:

$$P_{s_d} = N_d \, p_{s_d} = N_d \, \tau_d \ (1 - \tau_d)^{N_d - 1} (1 - \tau_v)^{N_v} \tag{3.12}$$

Now, if in P_{c_d} we only account for slots that contain collisions between data transmissions (crossed data and video collisions will be accounted in P_{c_v}) we can compute:

$$\begin{aligned} P_{c_d} &= (1 - \tau_v)^{N_v} \left[1 - \left(\frac{P_e}{(1 - \tau_v)^{N_v}} + \frac{P_{s_d}}{(1 - \tau_v)^{N_v}} \right) \right] \\ &= (1 - \tau_v)^{N_v} \left[1 - (1 - \tau_d)^{N_d} - N_d \, \tau_d \, (1 - \tau_d)^{N_d - 1} \right] \end{aligned} \tag{3.13}$$

where we have employed that the probability P_e of an empty slot occurs when there are no data nor video transmissions:

$$P_e = (1 - \tau_d)^{N_d} (1 - \tau_v)^{N_v} \tag{3.14}$$

Finally, the probability P_c that a random slot contains a collision can be expressed as:

$$P_c = P_{c_d} + P_{c_v} = 1 - (P_{s_d} + P_{s_v} + P_e) \tag{3.15}$$

and from the above we can obtain P_{c_v} as:

$$P_{c_v} = 1 - P_{s_d} - P_{c_d} - P_{s_v} - P_e \tag{3.16}$$

[1] p_{c_v} represents a different event and should not be confused with P_{c_v} defined before. While the former refers to the conditional probability that an attempt collides, the latter refers to the probability that there is a collision in a randomly chosen slot time.

3.2.2 Analysis of the τ

In order to compute τ_d and τ_v we have to consider that:

- Data is sent in saturation using DCF so τ_d can be computed according to [9] for each number of data stations N_d, using a minimum contention window CW_{min_d} and a maximum backoff stage m_d.

$$\tau_d = \frac{2\left(1-2p_{c_d}\right)}{\left(1-2p_{c_d}\right)\left(CW_{min_d}+1\right)+p_{c_d}CW_{min_d}\left[1-\left(2p_{c_d}\right)^{m_d}\right]} \tag{3.17}$$

- Video is sent in saturation using No-Ack/No-Retry multicast which in terms of throughput can also be modeled with [9] as a DCF in which no exponential backoff is used: $m_v = 0$. Under these conditions, τ_v can be computed as:

$$\tau_v = \frac{2}{CW_{min_v}+1} \tag{3.18}$$

3.3 GCR Unsolicited Retry Model

In this section, the N_v video stations are transmitting video using GCR Unsolicited Retry. Employing this mechanism for any number of retries R, the probability p_{s_v} that a video transmission attempt is successful can be computed as:

$$p_{s_v} = \tau_v\left(1-p_{c_v}\right)\sum_{i=0}^{R}\frac{1}{(R+1)}p_{c_v}^{i} = \frac{\tau_v\left(1-p_{c_v}^{R+1}\right)}{R+1} \tag{3.19}$$

which considers that a video transmission contains useful data for the throughput when (i) it does not collide, and (ii) all previous transmissions with the same content have collided. Note that the latter depends on the number of previous retransmissions, which is uniformly distributed between 0 and R (each case with probability $1/(R+1)$). We can see that the previous No-Ack/No-Retry mechanism is the special case for which $R = 0$.

The probability p_{s_d} that a data transmission attempt is successful does not change with respect to the case of No-Ack/No-Retry because a data station does not distinguish between the first video transmission or any of the retries that follow which makes τ_d and τ_v are equal to the previous case. However, the time slots T_{s_v} and T_{c_v} using GCR UR, have changed since now video is sent at the same rate than data traffic: $R_v = R_d$.
Employing p_{s_v} from equation 3.19 in the equations for the No-Ack/No-Retry model we can obtain the throughput for data and video stations when using GCR-UR mechanism.

3.4 GCR Directed Multicast Model

3.4.1 Throughput analysis

In this section, N_v video stations are transmitting video towards N_{rx} receiver stations each using GCR Directed Multicast. For each of the receivers we will have a unicast flow of video transmitting in saturation in DCF mode and hence, it can be studied following [9].

The throughput analysis for data traffic is the same as for No-Ack/No-Retry but for video traffic it has to be updated to account for the video flow to each receiver station as well for the new time slot durations. The throughput of video $r_{v_{DMS}}$ can be computed as:

$$r_{v_{DMS}} = \frac{1}{N_{rx}} \frac{P_{s_v} L_v}{T_{slot}} \tag{3.20}$$

considering that every video receiver will be served periodically with a video transmission after serving the rest of video receivers. The time slots for video using GCR DMS are now:

$$T_{c_v} = T_{PLCP} + \frac{H}{R_v} + \frac{L_v}{R_v} + DIFS \tag{3.21}$$

and

$$T_{s_v} = T_{PLCP} + \frac{H}{R_v} + \frac{L_v}{R_v} + SIFS + T_{PLCP} + \frac{ACK}{R_c} + DIFS \tag{3.22}$$

3.4.2 Analysis of the τ

GCR DMS performs a conversion multicast to unicast which employs the DCF mode. Therefore, we can directly apply the results of [9] to video traffic. For data traffic τ_d can be computed with equation (3.17) and, for video traffic using a minimum contention window CW_{min_v} and a maximum backoff stage m_v, τ_v can be computed for a video flow as:

$$\tau_v = \frac{2\left(1-2p_{c_v}\right)}{\left(1-2p_{c_v}\right)\left(CW_{min_v}+1\right)+p_{c_v}CW_{min_v}\left[1-\left(2p_{c_v}\right)^{m_v}\right]} \tag{3.23}$$

3.5 GCR Immediate Block Ack Model

3.5.1 Throughput Analysis

In this section, the N_v video station will transmit to the GCR group formed by the N_{rx} video stations a burst of N video frames using the GCR Immediate Block Ack mechanism. For simplicity reasons, in this and the next section we assume a single video source, $N_v = 1$, although the analysis could be easily extended to the case with multiple video sources. When colliding with a data frame, the first N' video frames which overlap with the data transmission will be lost, while the remaining N-N' video frames will be received successfully. According to that, p_{s_v} accounts for the average number of successful video frames transmitted in a slot time:

$$p_{s_v} = \tau_v \left[\left(1-p_{c_v}\right)N + p_{c_v}\left(N-N'\right)\right] \tag{3.24}$$

where following the explanation above, a burst transmits N successful frames in absence of collisions and N-N' otherwise. Therefore, the video throughput is:

$$r_{v_{iback}} = \frac{\tau_v\left[\left(1-p_{c_v}\right)N + p_{c_v}\left(N-N'\right)\right]L_v}{T_{slot}} \tag{3.25}$$

where the slot durations for video transmission need to be updated in T_{slot} as follows:

$$\begin{aligned} T_{s_v} = T_{c_v} =& N \left(T_{PLCP} + \frac{H}{R_v} + \frac{L_v}{R_v} + SIFS \right) + 2N_{rx} \left(T_{PLCP} + \frac{BACK}{R_c} \right) \\ &+ \left(2N_{rx} - 1 \right) SIFS + DIFS \end{aligned} \tag{3.26}$$

where $BACK$ is the length of a BlockAckReq or a BlockAck.
Data throughput and τ_v are the same than the computed for the No-Ack/No-Retry model as we are using CW_{min_v} and $m_v = 0$.

3.6 GCR Delayed Block Ack Model

3.6.1 Throughput analysis

In this section, bursts of N video frames are sent using the GCR Delayed Block Ack mechanism. According to that, a video source station and its N_{rx} receivers can be modeled as a unique *virtual video* station. For every video burst transmitted, the virtual station sends a BlockAckRequest and a BlockAck to each of the video receivers (a total of $2N_{rx}$ control frames) in case no collision occur. Only in the case that a collision occurs in one of the control frames, the virtual station doubles its CW_v.

- If we denote p_b the probability that the virtual station transmission attempt contains a burst then:

$$p_b = \frac{1}{1 + \frac{2N_{rx}}{1 - p_{c_v}}} \tag{3.27}$$

- Otherwise, the virtual station transmission attempt will contain a control frame with probability: $1 - p_b$

With the above, the probability p_{s_v} that a burst transmission attempt is successful can be computed as:

$$p_{s_v} = \tau_v \, p_b \left[\left(1 - p_{c_v} \right) N + p_{c_v} \left(N - N' \right) \right] \tag{3.28}$$

and the video throughput is:

$$r_{v_{dback}} = \frac{\tau_v \, p_b \left[\left(1 - p_{c_v} \right) N + p_{c_v} \left(N - N' \right) \right] \, L_v}{T_{slot}} \tag{3.29}$$

where T_{slot} needs to be updated to account for the two types of video transmissions, bursts of N frames and control frames:

$$T_{slot} = P_{s_d} T_{s_d} + P_{c_d} T_{c_d} + \tau_v \, p_b T_{N_{frames}} + \tau_v \left(1 - p_b \right) \left(1 - p_{c_v} \right) T_{BlockAcks} + P_e T_e \tag{3.30}$$

where:

$$T_{N_{frames}} = N \left(T_{PLCP} + \frac{H}{R_v} + \frac{L_v}{R_v} + SIFS \right) + DIFS \tag{3.31}$$

$$T_{BlockAcks} = T_{PLCP} + \frac{BACK}{R_c} + SIFS + T_{PLCP} + \frac{ACK}{R_c} + DIFS \tag{3.32}$$

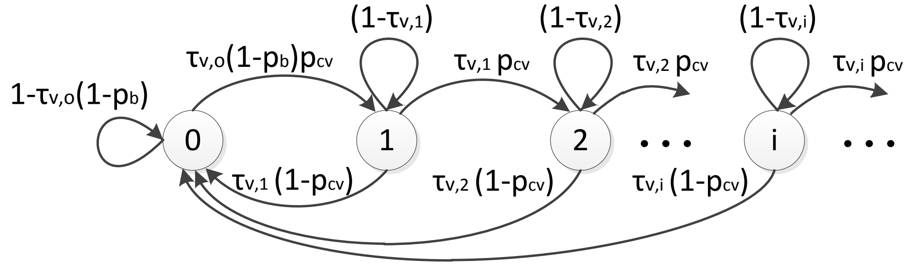

Figure 3.2: Markov chain model of the virtual video station.

3.6.2 Analysis of the τ

While in the previous cases the computation of τ followed the analysis of [9] with minor variations, the main difference of this case with the previous cases is that the CW_v is not always doubled after a failed attempt. In particular, after the transmission of a video burst, the next attempt which will be a BlockAckReq will use CW_{min_v} independently of whether the video burst transmission collided or not. In the following, we provide an analysis of τ that accounts for this behavior. As extending the Markov chain of [9] with this would result in a very complex Markov chain, we follow use a different and novel Markov chain with a much smaller number of states. Figure 3.2 models the backoff stage of the virtual video station with a discrete Markov chain which accounts for the number of collisions suffered by the control frames: BlockAckReq or BlockAck frames.
At state 0 the virtual station transmits in the next slot with probability:

$$\tau_{v,0} = \frac{2}{CW_{min_v} + 1} \tag{3.33}$$

in case the transmission attempt is not a control frame, the station remains at stage 0. Otherwise, if it is a control frame that suffers a collision, the station doubles its CW_v and moves to the next state. At next stages: (i) if it does not transmit, it remains in that state; (ii) if the transmission is succesful, it moves to stage 0 and resets its CW_v; (iii) if the transmission collides, it doubles the CW_v and moves to the next stage.
In general, at state i the transmission probability can be approximated using [7]:

$$\tau_{v,i} \approx \frac{\tau_{v,0}}{2^i} \tag{3.34}$$

If we denote p_i the probability of being at stage i, τ_v can be computed as the average:

$$\tau_v = \sum_{i=0}^{\infty} \tau_{v,i}\, p_i \tag{3.35}$$

In a discrete Markov chain the probability of being at a stage is a function of the probability of being at the previous stage and the transition probabilities so the probability p_1 of being at backoff stage 1 is the probability that being at stage 0 the video station transmits a control frame that collides, plus the probability that being already at stage 1, the video station does not transmit:

$$p_1 = p_0\, \tau_{v,0}\, (1 - p_b)\; p_{c_v} + p_1\, (1 - \tau_{v,1}) \tag{3.36}$$

using equation (3.34) we can write:

$$p_1 = 2p_{c_v}\, (1 - p_b)\; p_0 \tag{3.37}$$

similarly for p_2:

$$p_2 = p_1\, \tau_{v,1}\, p_{c_v} + p_2\, (1 - \tau_{v,2}) \tag{3.38}$$

using equations (3.34) and (3.37) we can write:

$$p_2 = 2p_{c_v} p_1 = (2p_{c_v})^2\, (1 - p_b)\; p_0 \tag{3.39}$$

so at stage i:

$$p_i = (2p_{c_v})^i\, (1 - p_b)\; p_0 \tag{3.40}$$

Applying the normalization condition: $\sum_{i=0}^{\infty} p_i = 1$ then:

$$p_0 + \sum_{i=1}^{\infty} (2p_{c_v})^i\, (1 - p_b)\; p_0 = 1 \tag{3.41}$$

which yields:

$$p_0 \left(1 + \frac{2p_{c_v}}{1 - 2p_{c_v}}\, (1 - p_b)\right) = 1 \tag{3.42}$$

and gives:

$$p_0 = \frac{1 - 2p_{c_v}}{1 - 2p_{c_v} p_b} \tag{3.43}$$

from equations (3.35) and (3.40):

$$\tau_v = \tau_{v,0}\, p_0 + \sum_{i=1}^{\infty} \frac{\tau_{v,0}}{2^i}\, (2p_{c_v})^i\, (1 - p_b)\; p_0 = \tau_{v,0}\, p_0 \left(\frac{1 - p_{c_v} p_b}{1 - p_{c_v}}\right) \tag{3.44}$$

finally, substituting τ_v and p_0:

$$\tau_v = \left(\frac{2}{CW_{min_v} + 1}\right) \left(\frac{1 - 2p_{c_v}}{1 - 2p_{c_v} p_b}\right) \left(\frac{1 - p_{c_v} p_b}{1 - p_{c_v}}\right) \tag{3.45}$$

In the case of data stations, their transmission probability τ_d is still given by [9]:

$$\tau_d = \frac{2\,(1 - 2p_{c_d})}{(1 - 2p_{c_d})\,(CW_{min_d} + 1) + p_{c_d} CW_{min_d}\left[1 - (2p_{c_d})^{m_d}\right]} \tag{3.46}$$

Therefore to find τ_d and τ_v we need to solve the system of non-linear equations formed by equations (3.45) and (3.46).

Chapter 4

Performance Evaluation

In order to perform the evaluation of the proposed models for the throughput of the new multicast mechanisms under specification in the IEEE 802.11aa draft, we have extended our simulation tool used in [13, 14]. This is a C/C++ discrete event simulator that accurately models the behavior of the IEEE 802.11g MAC layer. Additionally, we have also analyzed the reliability of each mechanism in the same scenario under more realistic constraints.
We show that our simulation results closely match those obtained analytically which validates the analysis presented in the previous section.

4.1 Throughput Performance

For the validation of the theoretical models we have particularized the scenario described in Figure 3.1 with:

- $N_v = 1$ video station is an AP that transmits video in saturation towards the variable number of receivers N_{rx}.
- $N_d = 1$, 4, 7, 10, 13 and 16 data stations transmit in saturation with a modulation rate of 54 Mbps while control frames (ACKs) are sent at 6 Mbps, packet length is 1500 bytes, $CW_{min_d} = 31$ and $m_d = 5$.
- For every N_d we perform a sweep on the number of video receiver stations that form the GCR group N_{rx} from 1 to 16 stations.

4.1.1 No-Ack/No-Retry

The legacy multicast service is generating saturation video traffic with a modulation rate of 6 Mbps with packets of $L_v = 1500$ bytes, $CW_{min_v} = 31$ and $m_v = 0$. Figure 4.1 shows the data throughput obtained with the analytical model and the simulations and Figure 4.2 shows it for the video throughput. We can note that in both cases, the throughput does not depend on the number of receiver stations but on the number of data stations, as No-Ack/No-Retry legacy multicast does not interact at all with the receiving stations. Although the No-Ack/No-Retry mechanism only transmits once each video frame, this transmission is done at 6 Mbps against the 54 Mbps of the data, which –according to the *performance anomaly* [10]– substantially reduces the throughput much below 54 Mbps.

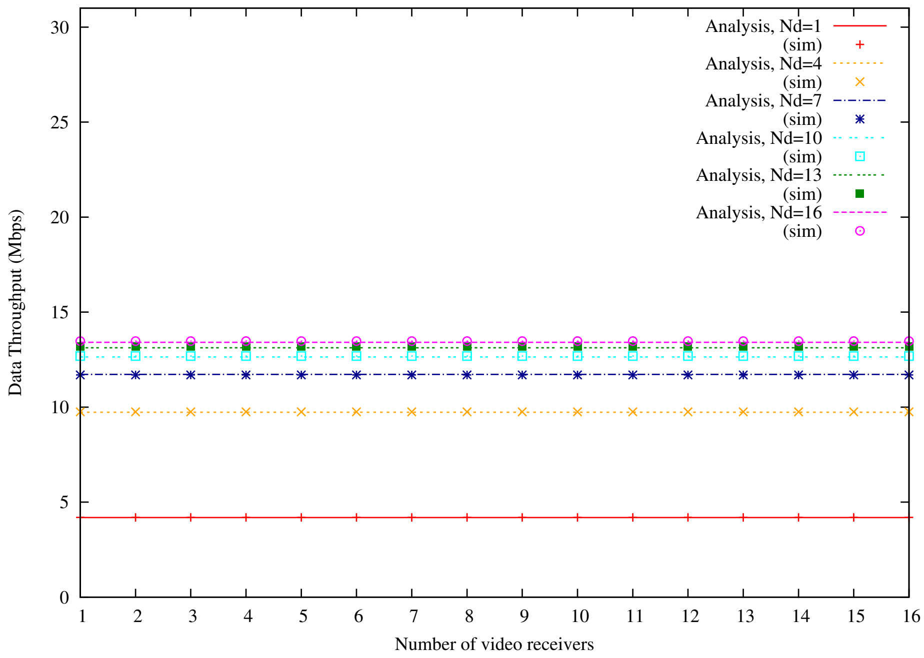

Figure 4.1: Data throughput using No-Ack/No-Retry

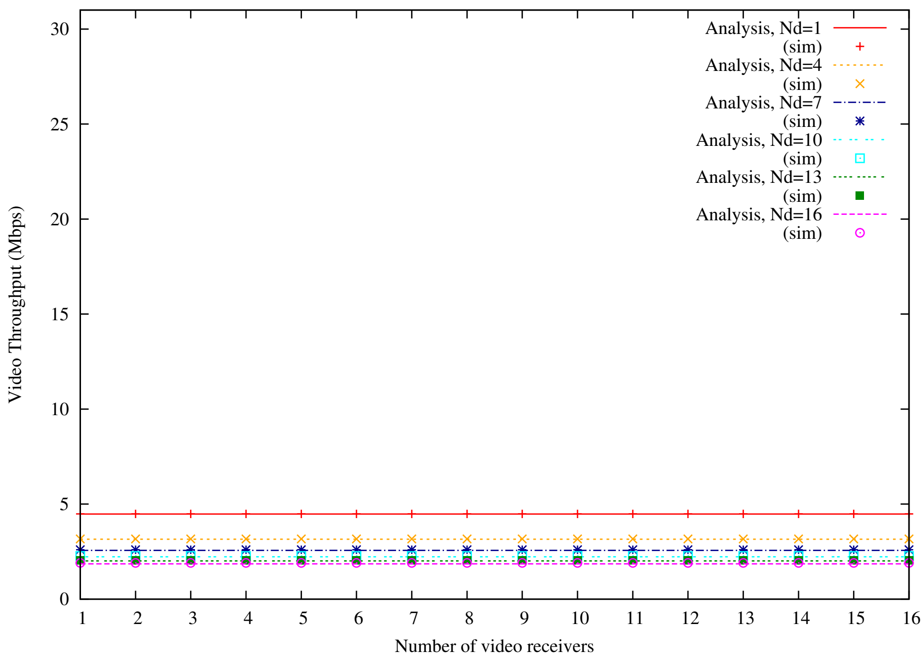

Figure 4.2: Video throughput using No-Ack/No-Retry

4.1.2 GCR Unsolicited Retry

To analyze the GCR Unsolicited Retry mode, we consider a scenario with $N_v = 1$ video station generating saturation video traffic with a modulation rate of 54 Mbps, packets of $L_v = 1500$ bytes, $CW_{min_v} = 31$ and $m_v = 0$. Figure 4.3 shows the data throughput for the analytical model and the simulations using GCR Unsolicited Retry for R=8 unsolicited retries and Figure 4.4 shows the video throughput. As in the No-Ack/No-Retry case, the throughput using GCR UR does not depend on the number of receiver stations. The use of a higher modulation coding scheme improves the data throughput up to around 25 Mbps. However, the overhead introduced by the GCR UR decreases the video performance as each frame is sent 9 times even if it has been already correctly transmitted.

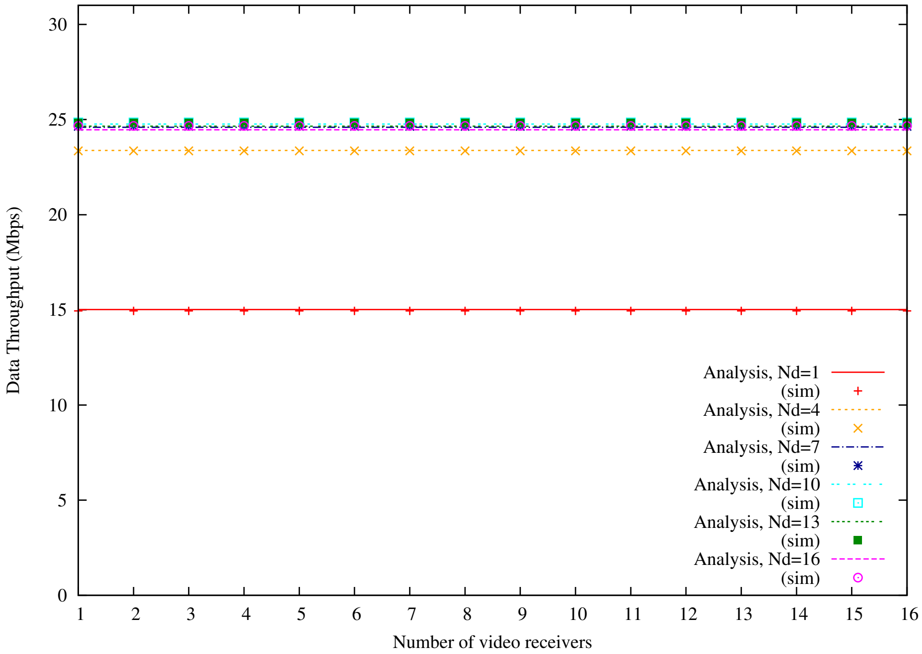

Figure 4.3: Data throughput using GCR Unsolicited Retries

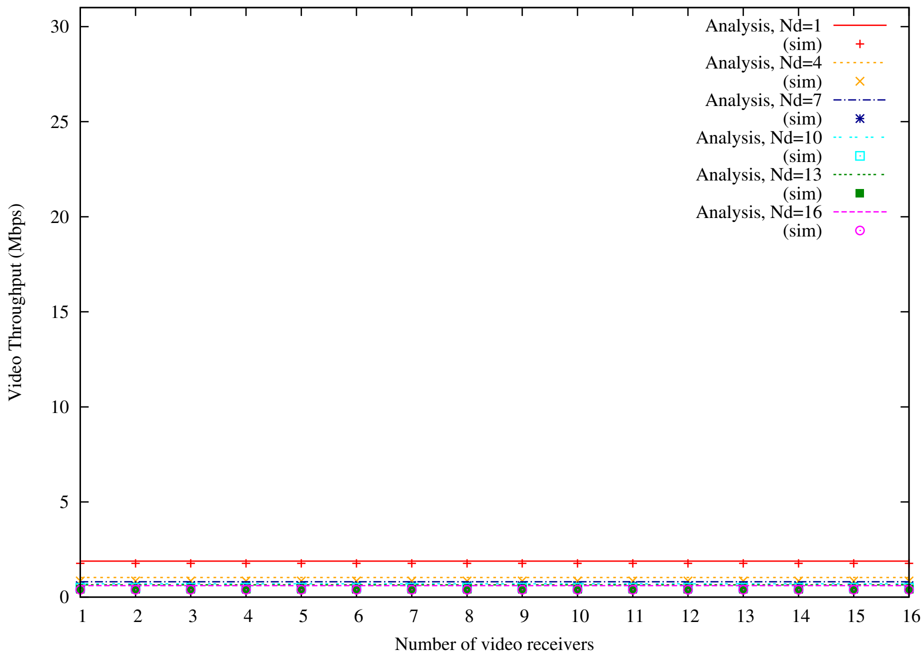

Figure 4.4: Video throughput using GCR Unsolicited Retries

4.1.3 GCR Directed Multicast Service

To analyze the GCR Directed Multicast mode, we consider a scenario with $N_v = 1$ video station generating saturation video traffic with a modulation rate of 54 Mbps, packets of $L_v = 1500$ bytes, $CW_{min_v} = 31$ and $m_v = 5$. Figure 4.5 shows the data throughput for the analytical model and the simulations using GCR Directed Mutlicast and Figure 4.6 shows it for the video throughput. In this case, only the data throughput is independent of the number of receivers. This is due to the fact that the interaction between the video transmitter the receivers is transparent to the data stations which do not know how many flows there are nor to which flow a video transmission corresponds. In the case of the video throughput, every new video receiver represents a new flow to serve which decreases the video throughput that can be achieved. Note however, that for 1 video receiver and 1 data station $N_d = 1$, the video throughput is equal to the data throughput as the video transmitter has the same opportunities as the data station to transmit a frame.

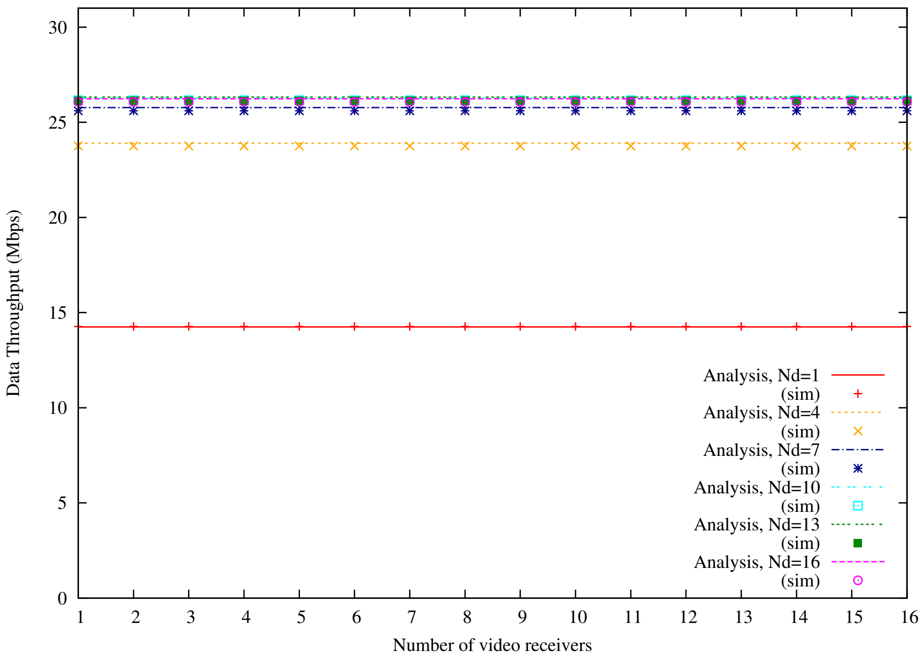

Figure 4.5: Data throughput using GCR Directed Multicast Service

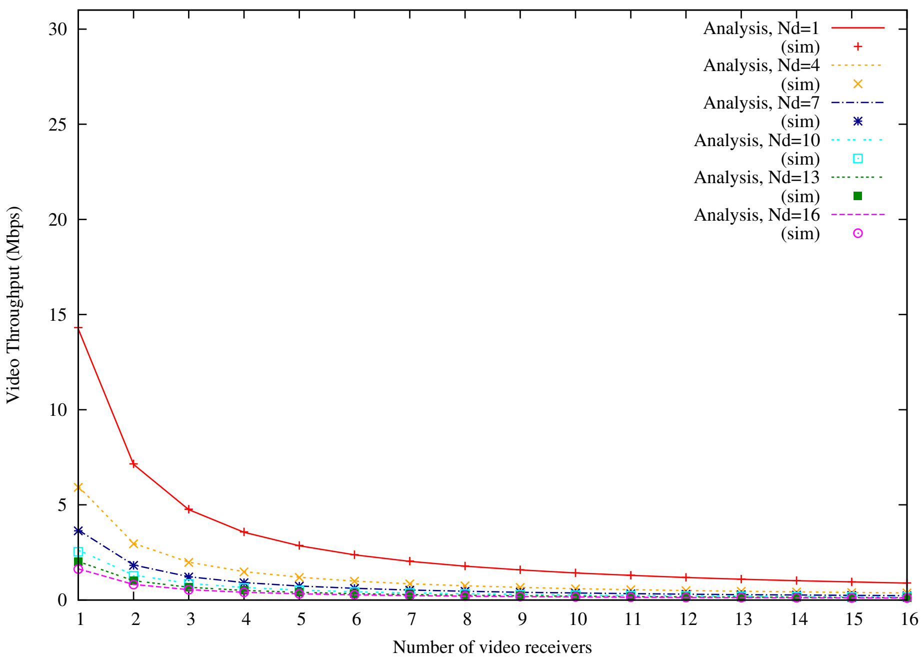

Figure 4.6: Video throughput using GCR Directed Multicast Service

4.1.4 GCR Immediate Block Ack

To analyze the GCR Immediate Block Ack mode, we consider a scenario with $N_v = 1$ video station generating saturation video traffic with a modulation rate of 54 Mbps, packets of $L_v = 1500$ bytes, $CW_{min_v} = 31$ and $m_v = 0$ for the video burst and control frames transmission. Figure 4.7 shows the data throughput for the analytical model and the simulations using GCR Immediate BlockAck mechanism when using 5 packet bursts and Figure 4.8 does it for the video throughput.
In this case, both data and video throughput are affected by the number of video receivers as the more video receivers the longer the time slot and video transmission exchange. This mechanism achieves the highest video throughput around 31 Mbps, as every successful video channel access represents 5 packets and a collision 4 since only the first packet of the burst would collide with a data transmission that could eventually occur only at the beginning of the same slot. However, the data throughput is severely affected as the increased length of transmissions reduces the amount of resources available for data traffic. Also note that when the number of data stations N_d increases, the data throughput and the video throughput converge to similar values.

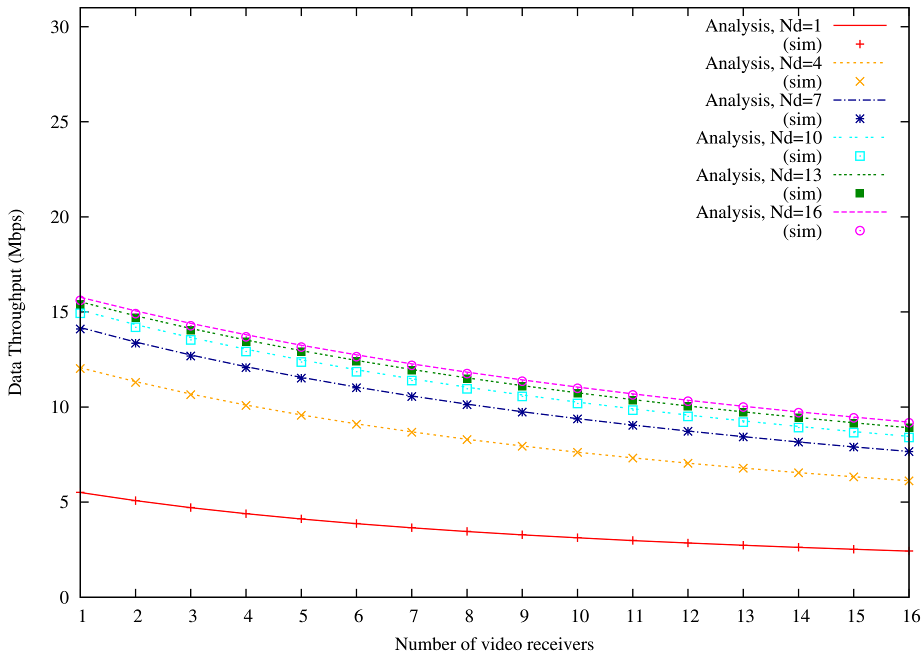

Figure 4.7: Data throughput using GCR Immediate BlockAck

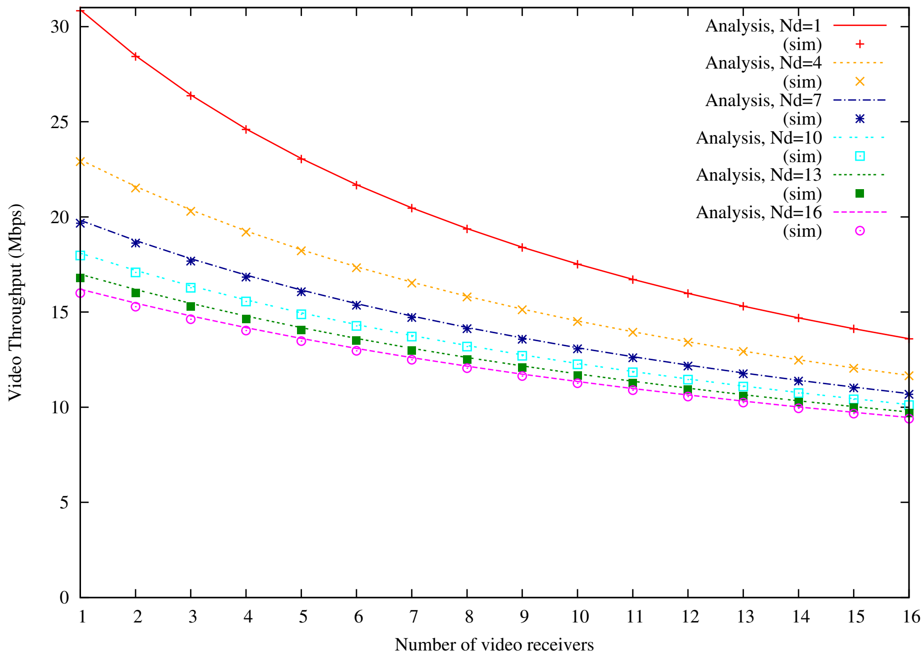

Figure 4.8: Video throughput using GCR Immediate BlockAck

4.1.5 GCR Delayed Block Ack

To analyze the GCR Delayed Block Ack mode, we consider a scenario with $N_v = 1$ video station generating saturation video traffic with a modulation rate of 54 Mbps with packets of $L_v = 1500$ bytes, $CW_{min_v} = 31$, $m_{v_b} = 0$ for the burst transmission and for the control frame transmission, $m_{v_{back}} = 5$. Figure 4.9 shows the data throughput for the analytical model and the simulations using GCR Delayed BlockAck mechanism when using 5 packet bursts and Figure 4.10 does it for the video throughput. This mechanism provides completely different results than the Immediate case due to the additional backoffs that are performed which allow the data stations to increase their throughput. We also note for this mechanism there is a slight discrepancy between the model and the simulation although simulation results still follow those obtained analytically fairly well.

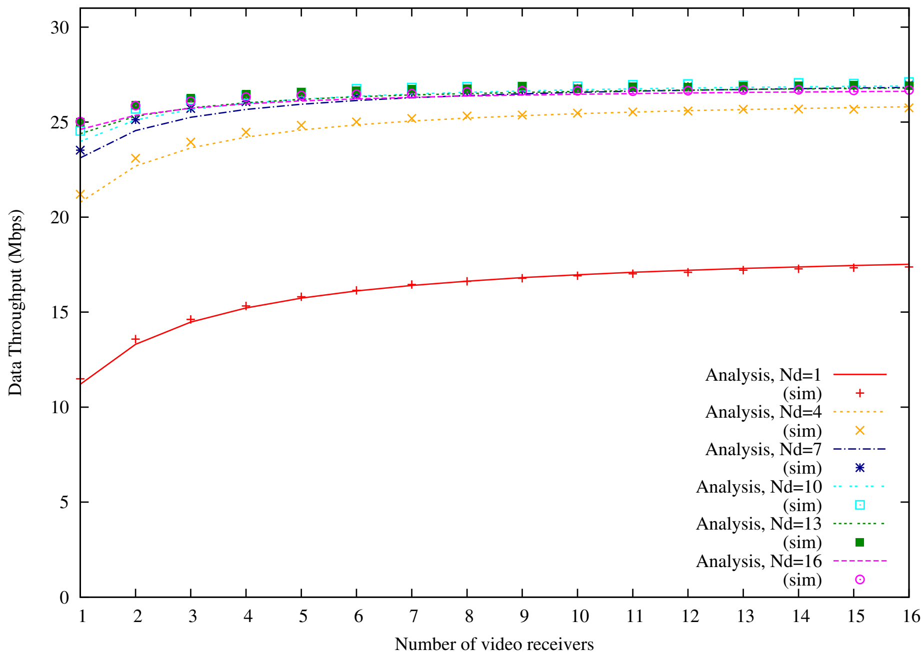

Figure 4.9: Data throughput using GCR Delayed BlockAck

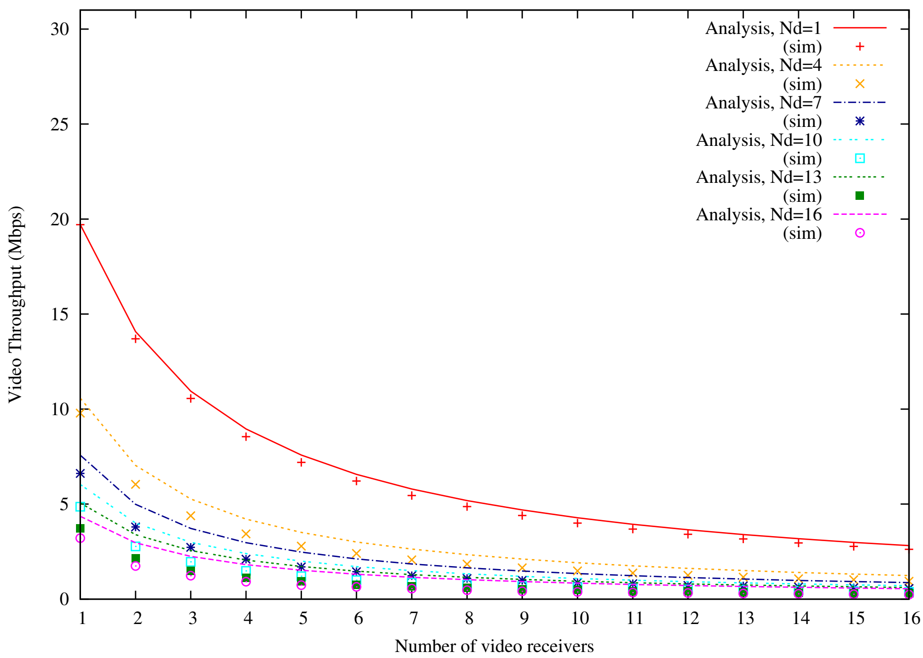

Figure 4.10: Video throughput using GCR Delayed BlockAck

4.2 Evaluation of the Reliability

In the previous section, we analyzed the throughput performance of the different schemes. In this section, we focus on an additional metric of interest which is the *reliability* of the multicast mechanisms, defined as the relative number of video frames that were correctly received. As our analysis does not address this metric, the results presented hereafter are limited to simulations. We consider the same scenario as for the throughput performance. However, video traffic is not sent in saturation anymore but:

- A Constant Bit Rate (CBR) video traffic of 1 Mbps generated in the AP by creating frame sizes of 1500 bytes every 12 ms.
- A maximum queue size in the AP of 100 frames.

4.2.1 No-Ack/No-Retry

Figure 4.11 shows the reliability when using the No-Ack/No-Retry mechanism. As expected, it is not able to provide 100 % reliability even in the case of just $N_d = 1$, as any collision will result in a packet lost. All losses are due to packet collisions and not to discarding in the queue as a 1 Mbps video is below the saturation limit for No-Ack/No-Retry shown in Figure 4.2 for any of the considered data stations. As for the throughput, this mechanism does not interact with the video receivers and so the reliability only decreases with the number of data traffic and remains independent of the number of video receivers.

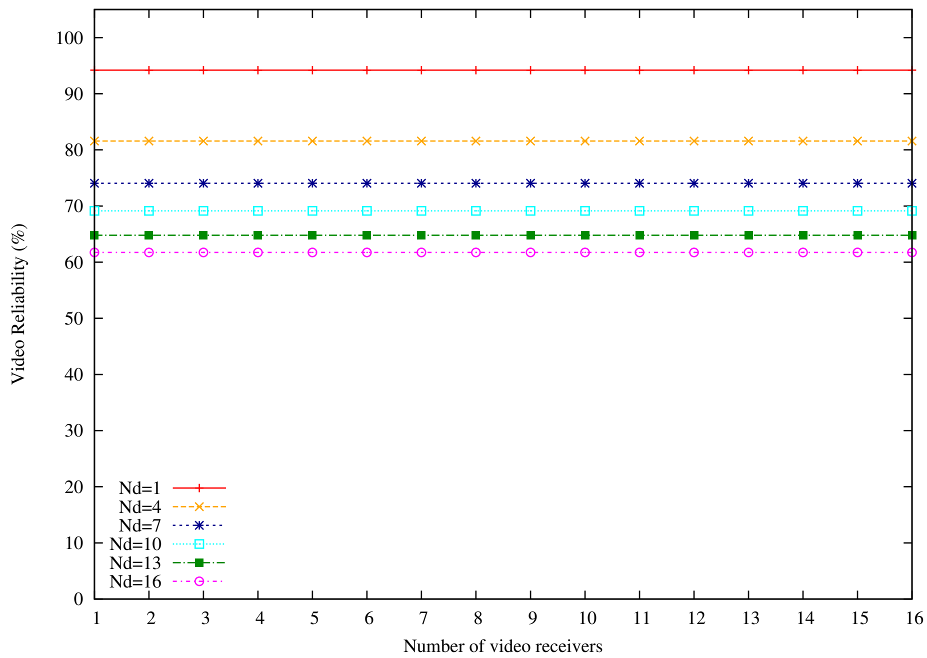

Figure 4.11: Video reliability using No-Ack/No-Retry

4.2.2 GCR Unsolicited Retry

Figure 4.12 shows the reliability when using the GCR Unsolicited Retry with $R = 8$. The mechanism does improve the performance as compared to the legacy multicast service achieving 100 % reliability up to 4 data stations then decreasing to approximately 60 % for a very congested WLAN. Note that for $N_d = 1$ and $N_d = 4$ the video throughput in Figure 4.4 is greater or equal than 1 Mbps so the performance is improved due to the use of preemptive retransmission that lessen the impact of collisions with data stations. For more data stations however, the overhead introduced by the retransmissions decreases the reliability as video frames are discarded due to queue overflow in the AP because the saturation throughput is lower than the 1 Mbps video bandwidth.

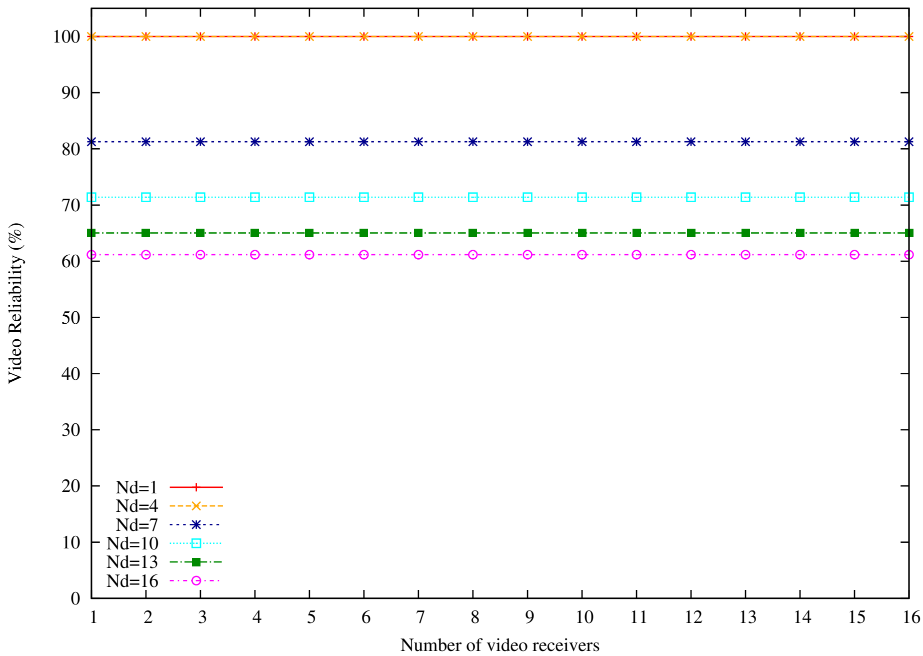

Figure 4.12: Video reliability using GCR Unsolicited Retry

4.2.3 GCR Directed Multicast

Figure 4.13 shows the reliability when using the GCR DMS. In this case, the reliability depends on the number of video receiver as this mechanism interacts with them. This mechanism provides a reliability of 100 % when the video saturation throughput shown in Figure 4.6 is bigger than the bandwidth of the transmitted video, 1 Mbps in our case. Below that, the reliability decreases as the number of data transmitters and the number of video receivers increase due to queue overflow.

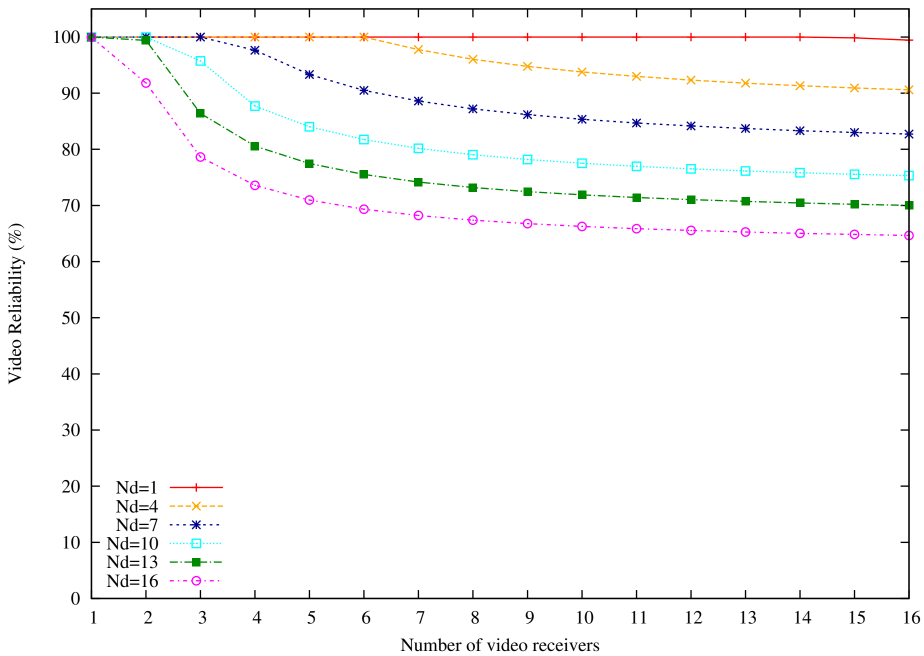

Figure 4.13: Video reliability using GCR Directed Multicast

4.2.4 GCR Immediate Block Ack

Figure 4.14 shows the reliability when using Immediate Block Ack with a 5 packet burst. This mechanism achieves a reliability greater than 90 % for any number of data stations and video receivers. In this case, as the saturation throughput shown in Figure 4.8 is always above 1 Mbps all packet losses are due to burst collisions in the channel that affect to single packets and not to discarding in the queue.

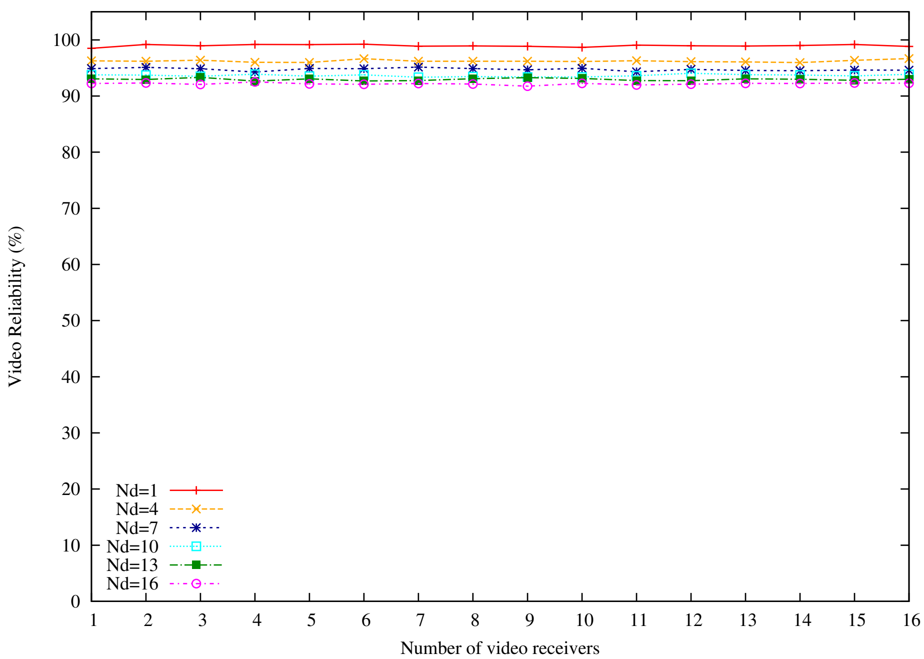

Figure 4.14: Video reliability using GCR Immediate Block Ack

4.2.5 GCR Delayed Block Ack

Figure 4.15 shows the reliability when using Delayed Block Ack with a 5 packet burst. This result is similar to the reliability of GCR DMS, for any number of data transmitters and video receivers, when the video bandwidth is smaller than the video throughput as shown in Figure 4.10, the reliability achieved in this case is the same as for Immediate Block Ack. However, the video bandwidth is bigger, the reliability decreases mainly because of packet discarding due to queue overflows.

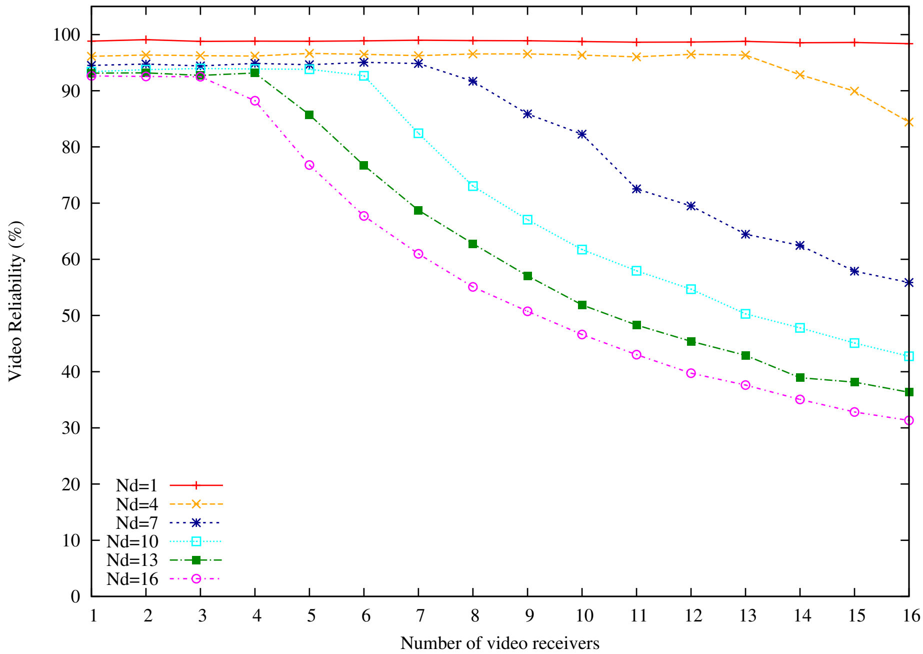

Figure 4.15: Video reliability using GCR Delayed Block Ack

Chapter 5

Summary

A key contribution of this Master thesis has been the derivation of an analytical model that allows to compute the throughput performance of the different schemes as a function of the number of video and data stations in the WLAN. This contribution represents a major step towards the optimal configuration of these mechanisms, as well as a major input towards the design of an algorithm to choose the most appropriate mechanism for a given scenario. Future steps include the modeling of the reliability and the extension of the performance evaluation of the proposed models.

We have performed the analysis and evaluation of the novel IEEE 802.11aa mechanisms in terms of throughput and reliability, for different WLAN scenarios, and compared them against the legacy multicast service of IEEE 802.11. We have confirmed that the new mechanisms are able to substantially improve performance, and that they provide different trade-offs considering their complexity, efficiency and reliability. We have identified the main limiting factors of each mechanism, that will support the derivation of guidelines to decide on the best mechanism for a given WLAN scenario.

According to these results, there seems to be no "best" service for video delivery, as in addition to their relative differences in terms of complexity, their relative performance also varies with the traffic conditions.

The main results, as compared against the previous sections, can be summarized as follows:

- Those mechanisms that do not interact at all with the number of receiving stations, i.e., legacy multicast and the GCR Unsolicited Retries offer the same performance independently of the number of receivers.
- On the other hand, the performance of those mechanisms that requires interactions with each of the receiving stations decreases as they increase.
- All GCR mechanisms provide a reliability above 90 % when they operate in non-saturation conditions. In that case, all packet losses are due to collisions in the channel. Otherwise, when the bandwidth of the transmitted video is above the saturation throughput of the employed mechanism the main reason of decreased reliability are discarding due to queue overflows.

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