Performance Evaluation of the Priority Resolution Scheme in PLC Networks

Cristina Cano and David Malone
Hamilton Institute
National University of Ireland, Maynooth
Co. Kildare, Ireland
Email: {cristina.cano,david.malone}@nuim.ie

***Abstract*—Power Line Communications standards, such as Homeplug and IEEE 1901, aim to provide strict channel access prioritisation in CSMA/CA mode. This is achieved by making lower-priority access categories postpone contention when packets belonging to categories with higher priority are pending for transmission. For this purpose, specific slots in which stations advertise the priority of the current packets to be transmitted are allocated. However, they are only present after the occurrence of successful frame exchanges. Thus, in lightly loaded conditions as well as after channel errors or collisions, the priority resolution mechanism is not employed. In this work, we evaluate the implications of these features on the QoS experienced by each access category. Results show the network provides a complex performance behaviour caused by the interdependence of higher-priority traffic contention and lower-priority traffic preemption.**

***Index Terms*—Power Line Communications, Homeplug, IEEE 1901, QoS, Access Categories, Priority Resolution.**

I. Introduction

Research efforts on Power Line Communication (PLC) networks have been mostly focused on the physical layer as the characteristics of PLC channels (including fading, impulsive noise and hidden/exposed terminal problems) impose several challenges on the physical aspects of the protocol [1]. However, the Medium Access Control (MAC) protocol, in contrast, has not received much attention by the research community.

PLC standards (we focus on Homeplug [2] and IEEE 1901 [3]) define a MAC procedure similar to the Distributed Coordination Function (DCF) defined in the IEEE 802.11 standard for Wireless Local Area Networks (WLANs) [4]. However, they derive from the vanilla DCF by adding a deferral counter that reduces the attempt rate when high contention is inferred on the channel. Additionally, priority differentiation is provided by the definition of 4 access categories (CAs) with different channel access parameters and a priority resolution scheme. The standardised priority resolution scheme is completely different from the QoS prioritisation defined in the IEEE 802.11e EDCA [5] standard. In Homeplug and IEEE 1901 MAC protocols, lower-priority frame transmissions are deferred when stations advertise that higher-priority CA frames are pending for transmission, and so aims to provide strict QoS guarantees. However, in contrast to the extensive evaluation of IEEE 802.11e, the QoS-enabling features of PLC standards have yet to be deeply evaluated in different scenarios, network conditions as well as varying traffic loads.

The main goal of this work is to extend the understanding of the priority resolution scheme defined in both Homeplug and IEEE 1901 MAC protocols. Specifically, we study the implications of using the priority resolution scheme only after successful frame exchanges which, as will be shown, has a substantial impact on network performance. To this aim, we perform a simulation-based evaluation in different scenarios and traffic conditions in order to get more insight on the performance of the network when different CAs are contending for the channel. Results show to which extent higher-priority categories are protected from low-priority traffic, how low-priority CAs are severely penalised and also highlight the complex behaviour of the network caused by the preemption of lower-priority transmissions being dependent on higher-priority traffic contention. The outcomes of this work are crucial to understand the implications of using the priority resolution mode of the standard.

The remainder of this article is organised as follows. In Section II we review previous work on traffic prioritisation in PLC. Then, in Section III we describe the channel access arbitration scheme defined in Homeplug and IEEE 1901 standards. The evaluation is presented in Section IV. Finally, some concluding remarks and future work on the implications of the standardised QoS-enabling features are provided.

II. Related Work

The priority resolution scheme of the Homeplug and IEEE 1901 MAC protocols has not yet been exhaustively studied. As far as the authors know, channel differentiation in PLC networks has only been partially evaluated in [6], [7], [8] and [9]. In [6], the performance of the network is studied when one priority user is present both in saturated and unsaturated conditions. Then, in [7] an experimental evaluation using a PLC testbed is performed, 1 to 4 high-priority flows contend for the channel in the presence of low-priority flows, CA3 and CA1 access categories are considered. In [8], the access differentiation is evaluated for different frame sizes and numbers of nodes. Finally, in [9], the performance while the number of nodes increases is evaluated for 3 different CAs.

In this work, we aim to extend previous work by providing an exhaustive evaluation in which the 4 different CAs are considered. Saturated and unsaturated conditions under varying packet arrival rates are also studied.

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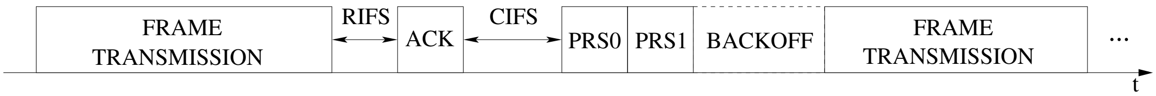


Fig. 1. Allocation of priority resolution slots (refer to [2] and [3]).

III. Channel Arbitration in Homeplug and IEEE 1901 Protocols

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mode of Homeplug and IEEE 1901 MAC protocols is based on the DCF defined in the IEEE 802.11 standard [4]. However, the original DCF backoff procedure is extended with the goal of reducing the collision probability when high contention is inferred on the channel. Additionally, priority differentiation is achieved by the definition of 4 different CAs with different channel access parameters and a strict priority resolution scheme. The backoff procedure as well as the priority resolution mechanism are described next.

A. Backoff Procedure

Each time a node has a new packet to transmit, the backoff stage ($i \in [0, m-1]$) is initialised to 0 and a random backoff is selected among $[0, W_0]$. The backoff countdown is frozen when activity is detected on the channel and restarted when the medium becomes idle again. The packet is actually transmitted when the backoff countdown expires. If an acknowledgement is received, the packet is considered successfully transmitted. Otherwise, the node starts the retransmission procedure: the backoff stage changes to $i = \min(i+1, m-1)$ and a new random backoff is selected among $[0, W_i]$, W_i being the contention window of backoff stage i.

Additionally, a new counter called the Deferral Counter (DC), is introduced. This counter is initialised at each backoff stage to M_i and decreased by one after overhearing a data packet or a collision. If a new packet or a collision are overheard and the value of the DC is equal to zero, the node acts as if a collision had happened: the backoff stage is increased if it has not yet reached its maximum value and a new backoff is selected among $[0, W_i]$. The goal of the DC is to avoid collisions when high contention is inferred by decreasing the aggressiveness of transmission attempts.

B. Priority Resolution Scheme

To provide channel access differentiation, 4 CAs are defined CA0–3. CA3 and CA2 share W_i and M_i values, as do CA1 and CA0 (see Table I). Two Priority Resolution Slots (called PRS0 and PRS1) are allocated at the end of successful frame exchanges as shown in Fig. 1. These priority resolution slots allow nodes to announce the priority of their packets pending for transmission. The highest priority (CA3) is signalled in both PRS0 and PRS1, the CA2 category is signalled in PRS0 only, CA1 in PRS1 and the lowest access category (CA0) does not have any notification interval associated. Following this approach, stations know whether there is a station with a frame pending for transmission that belongs to a higher category. In such a case, they do not contend for the channel expecting high-priority frames to be released.

TABLE I
Parameters of the different CAs in Homeplug and IEEE 1901 Protocols

Parameter	All CAs	Parameter	CA3/2	CA1/0
M_0	0	W_0	7	7
M_1	1	W_1	15	15
M_2	3	W_2	15	31
M_3	15	W_3	31	63

TABLE II
Parameters Homeplug 1.0

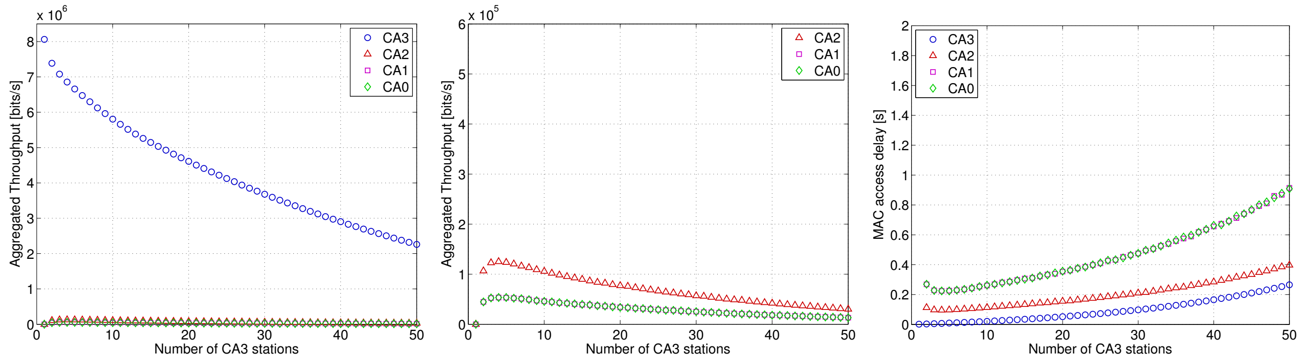
Parameter	Value in Homeplug 1.0
Data rate (R)	14 Mbps
ACK transmission time (T_{res})	72 μs
Slot time (σ)	35.84 μs
Data-ACK interframe space (RIFS)	26 μs
Contention interframe space (CIFS)	35.84 μs
Tx. indication slots (PRS0 = PRS1)	35.84 μs

Note that the previously described priority resolution scheme aims to provide strict channel access differentiation, i.e., using the priority resolution mechanism, packets with higher priority are always transmitted before lower-priority ones. However, the priority resolution scheme is only enabled after a successful frame exchange. The reader is referred to [2], [3], where it is defined that PRS are not present after: *i)* a collision, *ii)* frame transmissions resulting in erroneous receptions and *iii)* the detection of an empty channel for longer than an Extended InterFrame Space (EIFS)[1] period. Thus, in lightly loaded conditions and after collisions, the priority resolution scheme is not employed and channel access differentiation only occurs through the different MAC parameters of the access categories. As we will show, this severely impacts the performance of the network and its evaluation is the main goal of this work.

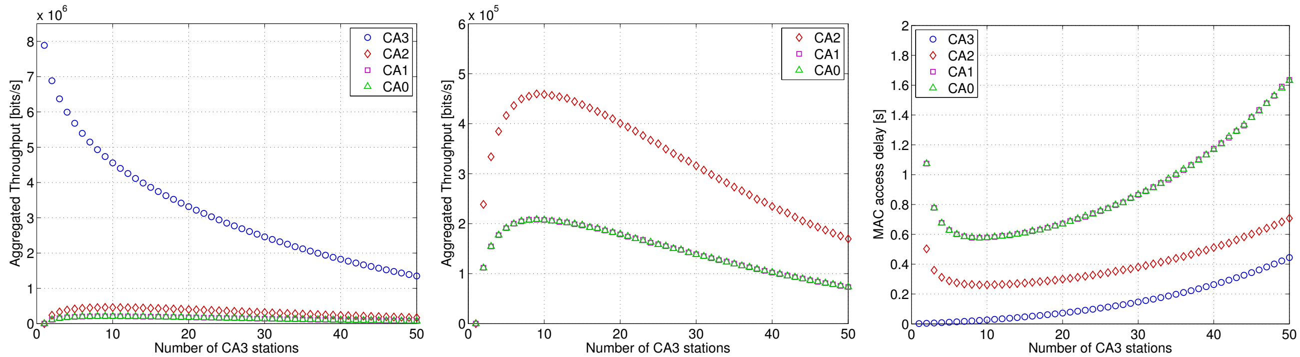
IV. Performance Evaluation

We evaluate the priority resolution scheme defined in Homeplug and IEEE 1901 along with the effect of the different parameters for channel access differentiation, the random backoff and the deferral counter. We consider: *i)* an infinite, or large enough to be considered infinite, buffer size and retry limit, *ii)* exponentially distributed interarrival of packets at the MAC layer, *iii)* ideal channel conditions, *iv)* that each station uses just a single CA for its packets and *v)* that all nodes are in mutual coverage range, that is, all nodes can overhear each other's transmissions. Furthermore, as we are interested in the implications of the priority resolution scheme, we do not

[1]EIFS is set to the duration of a frame transmission of maximum length.



(a) $n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 1$ (b) $n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 1$ (c) $n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 1$



(d) $n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 10$ (e) $n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 10$ (f) $n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 10$

Fig. 2. Results in saturated conditions for different configurations of n_{CAs}.

consider other optional or more sophisticated features of the standards that can influence the results, such as aggregation, frame bursting, contention free channel access, arbitration and flow control [2], [3].

Simulation results are obtained using a custom simulator based on the SENSE framework [10]. Parameters used are the ones defined in Homeplug MAC 1.0 and depicted in Table II. We consider the maximum payload size (1500 bytes) which corresponds to a frame transmission time equal to $1153.5\ \mu$s. The reader is referred to [11] for details on the calculation of the transmission time for this payload size. Contention windows and the starting value of the deferral counter used at each backoff stage are also the ones recommended by the standard (see Table I). Simulation time is set to 10000 and 100000 s for saturated and unsaturated conditions, respectively.

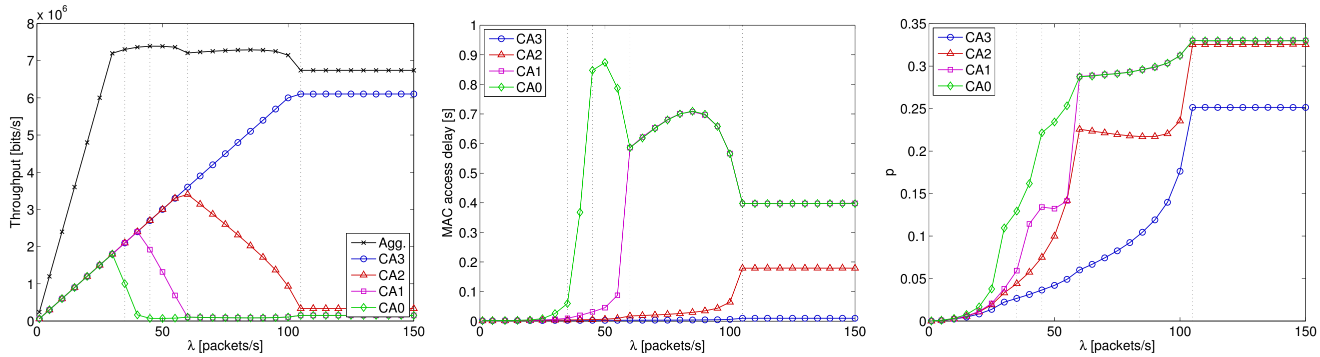
A. Saturated Conditions

Fig. 2 shows the performance results in saturated conditions when the number of stations generating packets that belong to the CA3 access category (n_{CA3}) varies. Two different configurations of CA2–CA0 are considered: setting $n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 1$ and $n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 10$. The aggregated throughput and MAC access delay of all CAs is shown in Fig. 2(a) and 2(d) and Fig. 2(c) and 2(f), respectively. A closer look at the aggregated throughput obtained for CA2–CA0 is depicted in Fig. 2(b) and 2(e).

First observe that lower-priority stations are effectively not able to transmit when there is only one CA3 station contending for the channel. This is caused by the priority resolution scheme taking always place. Recall that the CA3 station has always a packet to transmit, there are no collisions taking place and we have assumed no channel errors. Thus, the CA3 station is always acquiring the channel by making the others refrain from transmission through the use of the PRSs.

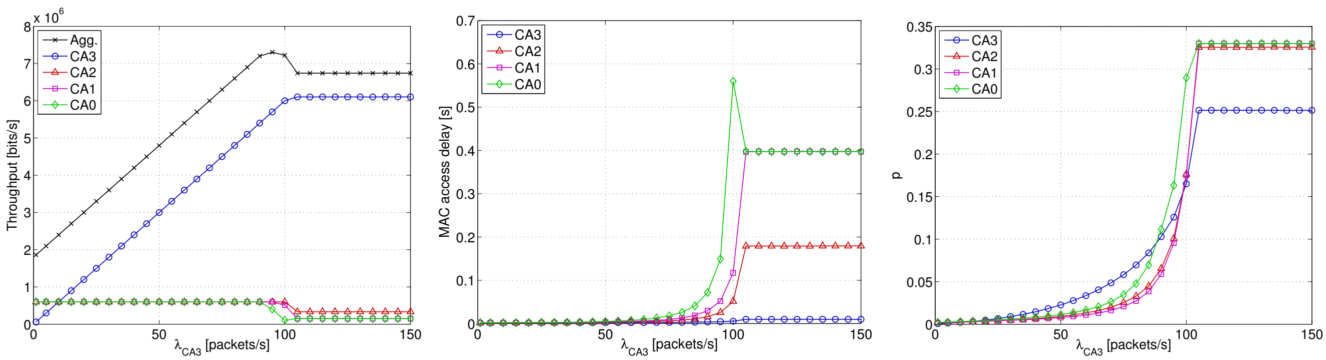
When the number of CA3 stations increases, lower-priority stations first face an increase in their throughput and a reduction of delay (Fig. 2(b), 2(c), 2(e) and 2(f)) caused by the augmented channel attempt opportunities due to the increased collision probability of CA3 frames that moves the system to a non-priority-resolution contention. However, once more than about 3 and 8 CA3 stations are present in the first and second scenario, respectively, the higher number of CA3 stations contending for the channel in the non-priority resolution mode makes the throughput and delay of lower-priority stations degrade. Note also that, given that lower-priority stations only access the channel during non-priority-resolution mode, CA0 and CA1 performance results coincide as they share W_i and M_i parameters. In contrast, CA2 stations are able to obtain a better performance due to the higher attempt probability derived from a reduced W_i in backoff stages 2 and 3.

Finally, it is also worth observing that the aggregated throughput of lower-priority stations increases when more stations belonging to these categories contend for the channel (compare the results shown in Fig. 2(b) and 2(e)). Although



(a) Throughput (b) MAC access delay (c) Conditional collision probability

Fig. 3. Results in unsaturated conditions increasing λ of all CAs ($n_{\text{CA3}} = n_{\text{CA2}} = n_{\text{CA1}} = n_{\text{CA0}} = 5$).



(a) Throughput (b) MAC access delay (c) Conditional collision probability

Fig. 4. Results in unsaturated conditions increasing λ_{CA3} while keeping the others equal to 10 packets/s ($n_{\text{CA3}} = n_{\text{CA2}} = n_{\text{CA1}} = n_{\text{CA0}} = 5$).

the per-station throughput is reduced, there is an overall gain caused by the increased probability of acquiring the channel when competing with the highest-priority stations.

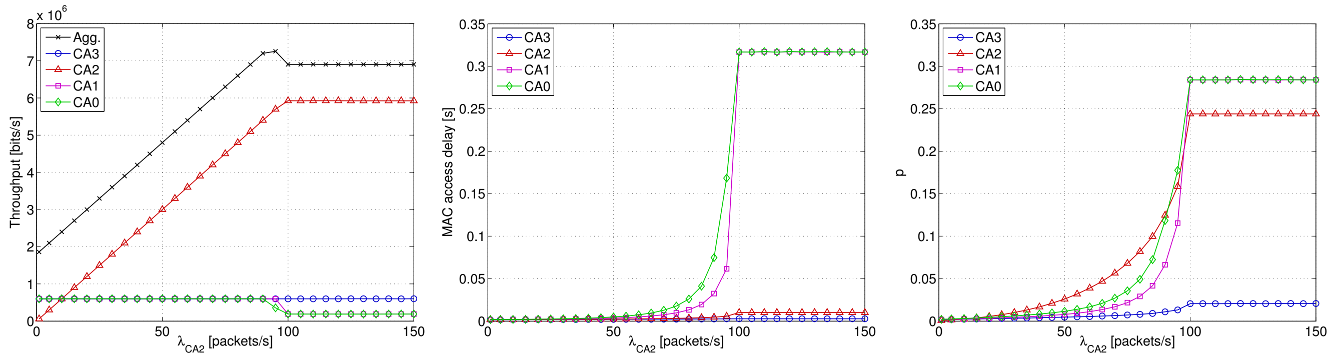
B. Unsaturated Conditions

1) Simultaneous Increase of Traffic Load: For the unsaturated case, we first increase the packet arrival rate (λ) simultaneously at all CAs. Results per CA (throughput, MAC access delay and conditional collision probability) as well as aggregated throughput (labelled as *Agg.*) when the number of nodes at each CA is equal to 5 are depicted in Fig. 3. Results demonstrate the complex behaviour of the performance as the packet arrival rates vary. We are going to describe the results found in detail in order to understand the complex features observed. To facilitate the next description, we also plot (vertical dotted lines) the first point at which each CA is saturated, these instants correspond to a change of behaviour.

Due to its lower channel attempt probability, CA0 is the first access category to saturate (first vertical dotted line). After this point, the performance obtained by CA0 stations starts to substantially degrade (Fig. 3(a) and 3(b)). After this, CA0 stations face a decrease in their channel attempt rate caused by: *i)* the higher packet arrival rates at other access categories, *ii)* higher inter-category contention (when the priority resolution is not enabled) and, *iii)* higher intra-category contention. The reduced channel attempt probability reduces the rate at which the conditional collision probability increases, explaining the uneven increase in collision probability seen in Fig. 3(c).

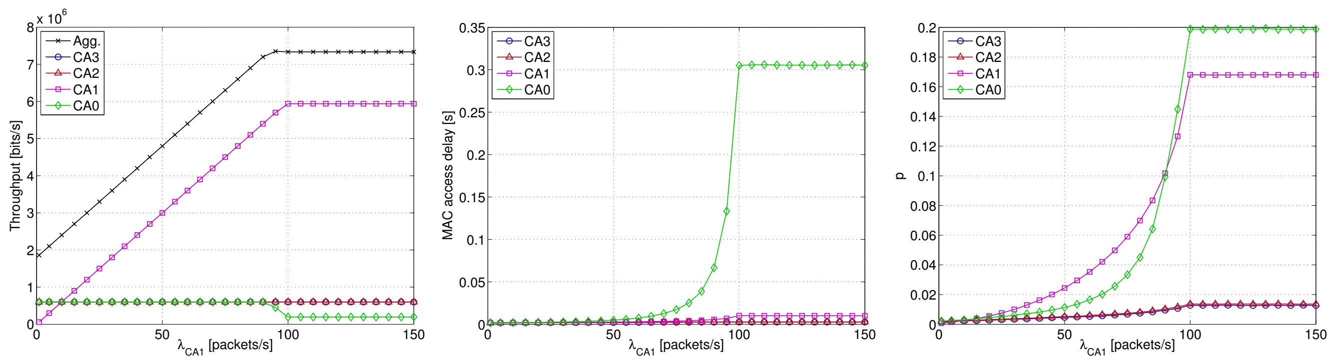
When stations with frames belonging to CA1 saturate (second vertical dotted line), CA0 traffic first obtains worse performance but throughput and delay improve as the packet arrival rate keeps increasing. When CA1 stations saturate, these frames will always be transmitted instead of CA0 frames when the priority resolution mode is enabled (observe again the reduction of the conditional collision probability increase rate). However, as packet arrival rates continue to increase, a higher number of collisions leads the system to operate in a non-priority resolution fashion with a higher probability. Thus, making the performance of CA0 improve as the chance to acquire the channel becomes closer to that of CA1.

Then, after the stations in CA2 saturate (third vertical dotted line), the performance obtained by CA0 and CA1 coincide as they are only able to acquire the channel when the priority resolution scheme is not used. Thus, as already seen in the saturated case, the sharing of MAC parameters of these two access categories results in the same channel access probabilities. The same effect seen when CA1 saturates is observed here: first, CA0 and CA1 face a degradation of their performance but, as the contention keeps increasing, they have more chances to transmit through the non-priority resolution mode.



(a) Throughput (b) MAC access delay (c) Conditional collision probability

Fig. 5. Results in unsaturated conditions increasing λ_{CA2} while keeping the others equal to 10 packets/s ($n_{\mathrm{CA3}} = n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 5$).



(a) Throughput (b) MAC access delay (c) Conditional collision probability

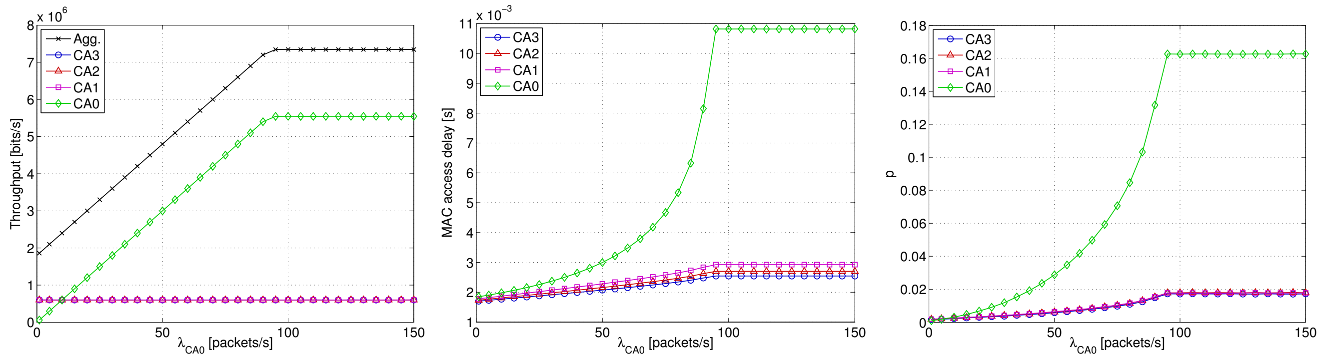
Fig. 6. Results in unsaturated conditions increasing λ_{CA1} while keeping the others equal to 10 packets/s ($n_{\mathrm{CA3}} = n_{\mathrm{CA2}} = n_{\mathrm{CA1}} = n_{\mathrm{CA0}} = 5$).

Finally, when CA3 stations saturate, the other access categories are only able to access the channel after a collision of the highest-priority stations. Observe that, the aggregated saturation throughput (shown in Fig. 3(a)) is smaller than the throughput obtained when CA3 is not saturated. This effect appears due to the smaller conditional collision probability that higher-priority stations face by making use of the priority resolution scheme that reduces the number of stations participating in the contention.

2) Increase of CA3 Traffic Load: In the next scenario we set the number of contending stations per access category to 5 and keep the packet arrival rate of CA2–0 fixed at 10 packets/s while varying the packet arrival rate of CA3 stations. Results (throughput, MAC access delay and conditional collision probability) are depicted in Fig. 4. Note that, stations with CA0 frames saturate right before CA1 ones do, as well as stations with CA1 frames saturate before CA2 ones (Fig. 4(a) and 4(b)). Again, we observe a degradation followed by an improvement of the performance for CA0 stations, complemented with a reduced increase of the conditional collision probability (implying lower channel access attempt rate, see Fig. 4(c)), right after CA1 stations face saturation. As also seen in the last scenario, the aggregated throughput (Fig. 4(a)) shows a higher value before CA3 stations are saturated. The lower collision probability among CA3 stations before saturation allows to work in the priority resolution scheme more often with a reduced number of overall competing stations.

3) Increase of CA2 Traffic Load: Now we consider the same scenario but varying the packet arrival rate of CA2 traffic instead of the one of CA3. Results are shown in Fig. 5. Observe now that, although suffering an increased conditional collision probability as the CA2 arrival rate increases (due to transmissions not using the priority resolution scheme), CA3 stations are able to transmit the amount of traffic they generate regardless of the load on CA2. In contrast, CA0 and CA1 saturate right before CA2 does. Note also the pre-saturation throughput peak in aggregated throughput that takes place due to the benefit of using the priority resolution scheme that removes CA0 and CA1 stations from the contention.

4) Increase of CA1 Traffic Load: The results of varying only the packet arrival rate of CA1 stations is now depicted in Fig. 6. Observe how in this case, CA3 and CA2 face a slight increase in the conditional collision probability (again, due to transmissions not using the priority resolution scheme) but are still able to transmit all the traffic generated. On the contrary, CA0 stations become saturated right before CA1 stations do. Moreover, now observe that when saturated, the CA0 conditional collision probability is higher than the one faced by CA1 stations. This effect, is caused by the priority



(a) Throughput (b) MAC access delay (c) Conditional collision probability

Fig. 7. Results in unsaturated conditions increasing λ_{CA0} while keeping the others equal to 10 packets/s ($n_{\text{CA3}} = n_{\text{CA2}} = n_{\text{CA1}} = n_{\text{CA0}} = 5$).

resolution scheme that increases the success rate of CA1 frames compared to CA0 traffic. It is also worth observing that the pre-saturation throughput peak is not as prominent as in the last scenarios evaluated since now only CA0 stations are the ones that refrain from transmission while using the priority resolution scheme.

5) Increase of CA0 Traffic Load: When varying CA0 packet arrival rate (see Fig. 7), all other access categories are able to transmit all packets generated, although facing a slight increase in MAC access delay and conditional collision probability. Note also that in this specific scenario there is no pre-saturation throughput peak as CA0 stations are not able to take advantage of the priority resolution scheme. Thus, no benefit appears in throughput at a lower CA0 conditional collision probability if compared to the saturated one.

V. Final Remarks

In this work we have studied the performance obtained using the priority resolution scheme along with different channel access parameters as defined in Homeplug and IEEE 1901 standards. Results show a complex behaviour, highlighting that QoS guarantees of high-priority traffic as well as the penalty for low-priority traffic vary with the high-priority traffic contention. On one hand, lower-priority traffic is not effectively served under high higher-priority traffic conditions. However, contention in higher-priority categories allows lower-priority ones to increase their share. Those implications are crucial to be considered when using the priority resolution mode.

Future work includes the evaluation of the effect of channel errors and other more sophisticated features of the standards such as aggregation and bursting. We have only considered the effect of channel contention on the priority resolution scheme. However, channel errors also move the system to work in a non-priority resolution mode. The effect of channel errors is worth to be evaluated as it may further increase the complex behaviour of the performance of the network. Testbed experimentation can provide more insight regarding this issue. Along this line, we may also find priority resolution slots not being properly detected in practical experimentation. Thus, the priority resolution scheme may not work as predicted. Moreover, as differences in signalling in these slots vary in the different access categories we may encounter differences among correct detection at each access category due to switching times between reception/transmission modes. We also expect aggregation and bursting to have an impact on the share of resources obtained, especially considering different limits based on the category of the packets to transmit.

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