

When Priority Resolution Goes Way Too Far: An Experimental Evaluation in PLC Networks

Cristina Cano, David Malone

Hamilton Institute, National University of Ireland, Maynooth, Ireland.

Abstract—Power Line Communication (PLC) devices are increasingly used and available. However, research carried out at the Medium Access Control (MAC) layer is limited. This article addresses Quality of Service (QoS) mechanisms defined in the widely implemented Homeplug and IEEE 1901 standards. By means of a testbed constructed from off-the-shelf components we identify a number of issues with a potentially significant impact on user satisfaction: *i)* a pronounced starvation and variability of lower-priority traffic when different access categories are combined and *ii)* an oscillatory behaviour in higher-priority and high-traffic configurations. We also determine the underlying causes of such findings and propose possible solutions. Our contributions are of relevance to both the research community and manufacturers, as we identify crucial aspects to be revisited in order to guarantee successful advancement and further adoption of the technology.

Index Terms—PLC, Homeplug, IEEE 1901, QoS.

I. INTRODUCTION

PLC networks have recently experienced increased deployment. For instance, the chip manufacturer Qualcomm Atheros reports over 100M Homeplug networking devices shipped and expects this number to grow in 32% each year from 2011 to 2017 [1]. The harsh physical conditions of power line channels imposed problems that restrained penetration of early implementations. Current solutions based on Homeplug AV [2] and IEEE 1901 [3] can now provide data rates of 500 Mbps and operate in a range of different scenarios. However, there is limited research carried out at the MAC layer.

The priority resolution scheme defined in the Homeplug [4] and IEEE 1901 [3] standards provides channel differentiation by allowing higher-priority packets to be transmitted before lower-priority ones. However, that strict priority resolution scheme can only be achieved after a successful packet transmission. In this article, we extend the work in [5] providing more insight by means of a testbed formed by off-the-shelf devices. On one hand, we show how this strict prioritisation mechanism completely starves lower-priority flows and also how the blocking of control messages, which are not always transmitted at the highest priority, causes an oscillatory behaviour of high-priority flows in heavy-traffic conditions. On the other hand, we evaluate the impact on traffic differentiation of current aggregation and buffer management techniques implemented by vendors. The outcomes of this work are relevant not only to design solutions to provide satisfactory user experience but to identify the vulnerability of PLC networks to denial-of-service attacks. In detail, the contributions of this work are:

- 1) Identifying the behaviour of the prioritisation mechanism of Homeplug/IEEE 1901 MAC using off-the-shelf devices. This is achieved by analysing the performance of a **PLC testbed** in a comprehensive range of scenarios, including key combinations of access categories (CAs).
- 2) Identifying the **significant starvation and variability** faced by lower-priority traffic and the **oscillatory behaviour** of higher-priority flows under high contention.
- 3) Analysing the influence of **aggregation and buffer management** techniques implemented in off-the-shelf hardware in QoS differentiation.
- 4) Proposing **solutions to ameliorate the negative aspects** found in the framework of Homeplug/IEEE 1901 MAC. Thus, the solutions provided can either be accommodated in the standards by subtle modifications and/or implemented as vendor-specific techniques.

The remainder of this article is organised as follows. In Section II, we provide related work on access differentiation. Then, in Section III, we describe the backoff procedure and priority resolution scheme defined in Homeplug/IEEE 1901. Insight obtained from an off-the-shelf testbed is described in Section IV. Finally, we conclude with some final remarks along with our proposed solutions to the identified problems.

II. RELATED WORK

The priority resolution scheme defined in the Homeplug and IEEE 1901 standards has not yet been exhaustively studied. As far as we 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. 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 number of nodes. Then, in [9], the performance while the number of nodes increases is evaluated for 3 different CAs.

In [5], we evaluated the performance via simulations considering the 4 different CAs, as well as saturated and unsaturated conditions. In this work we verify whether the tendencies observed in simulations are found in an off-the-shelf testbed and obtain more insight into other aspects which are normally neglected in theoretical evaluations but that directly impact network performance and priority differentiation. These outcomes, which have a significant impact on user satisfaction, have not yet been identified in previous literature. Thus, this

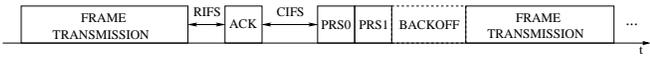


Fig. 1. Allocation of priority resolution slots (refer to [4] and [3]).

work is a starting point for improved mechanisms to ameliorate the negative issues we identify, which are of relevance to standard amendments and vendor-specific techniques.

III. THE PLC STANDARD

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mode of the Homeplug and IEEE 1901 MAC protocols extends the DCF channel access procedure defined in the IEEE 802.11 standard [10]. Compared to DCF, the Homeplug/IEEE 1901 MAC protocol: *i*) makes more effort to avoid collisions via an additional deferral counter and *ii*) defines a strict priority resolution scheme. The use of the deferral counter aims to infer whether high contention is present on the channel and attempts to reduce the channel attempt probability. This ability to increase performance is studied in [11] for different scenarios. On our second point, service differentiation, is achieved by defining 4 CAs with different channel access parameters and a strict priority resolution scheme. Next we describe the backoff procedure considering the deferral counter, the priority resolution scheme defined and the concept of tone map in Homeplug/IEEE 1901.

A. Backoff Procedure

As with Wi-Fi, when a node has a new packet to transmit, the backoff stage ($i \in [1, m]$)¹ is initialised to 1 and a random backoff is selected among $[0, W_1]$. The backoff countdown is frozen when activity is detected on the channel and restarted when the medium becomes idle again. The packet is transmitted when the backoff countdown expires. If an acknowledgement is received, the packet is considered successfully transmitted. Otherwise, the node starts the re-transmission procedure: the backoff stage changes to $i = \min(i + 1, m)$ and a new random backoff is selected among $[0, W_i]$, W_i being the contention window of backoff stage i .

In contrast to 802.11, an additional Deferral Counter (DC), is introduced. This counter is initialised at each backoff stage to M_i (see Table I) and decremented on 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.

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

¹Actually, ($i \in [0, m - 1]$) but indexes have been relabelled here for clarity of illustration.

TABLE I
CA PARAMETERS IN HOMEPLUG/IEEE 1901

Parameter	All CAs	Parameter	CA3/2	CA1/0
M_1	0	W_1	7	7
M_2	1	W_2	15	15
M_3	3	W_3	15	31
M_4	15	W_4	31	63

exchanges as shown in Fig. 1. These slots allow nodes to announce the priority of packets pending transmission. The highest priority (CA3) is signalled by transmitting a symbol in both PRS0 and PRS1, the CA2 category is signalled in PRS0 only. CA1 signals in PRS1, if PRS0 was empty, and the lowest access category (CA0) does not signal at all. Following this approach, stations know if there is a station with a frame that belongs to a higher CA. In such a case, they do not contend for the channel, allowing high-priority frames to be released.

Note that this resolution scheme aims to provide strict 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 invoked after successful frame exchanges. The standards [4], [3] suggest 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) period². Thus, in lightly loaded conditions and after collisions or channel errors, the priority resolution scheme is not employed and channel access differentiation only occurs through the different parameters of the access categories. Thus, we expect strict prioritisation if we have a single station in a high CA, but less strict prioritisation if multiple stations are in the highest CA because of collisions, as shown in [5] via simulations.

C. Tone Map Information

The modulation and coding scheme commonly used by Homeplug/IEEE 1901 uses OFDM with a large number of carriers. The modulation scheme used on the carriers is negotiated between transmitters and receivers through channel sounding and a frame exchange to agree a *tone map*. Tone maps are typically renegotiated every 30s to account for possible changes in the PLC medium.

IV. INSIGHTS FROM A PLC TESTBED

In this section, we obtain insight into network performance from an off-the-shelf PLC testbed by evaluating the interplay between high-priority traffic and control messages as well as by considering nonsaturated traffic and the aggregation/buffer management techniques implemented by vendors.

A. Testbed Setup

We have used Zyxel PLA4215 Power Line adapters with INT7400 chipset and firmware INT7400-MAC-5-2-5203-00-907-20110320-FINAL-B. In order to isolate the devices from interference in the mains, which can have an influence on

²EIFS is set to the duration of a frame transmission of maximum length.

results, we have connected them using an uninterruptible power supply unit. The PLC adapters have been attached to the Gigabit Ethernet port of Net6501-70 Soekris boxes.

The *iperf* traffic generator has been used to generate traffic on the devices and to measure the throughput at the receiver. Additionally, in order to obtain insight into the number of access opportunities won by stations, rather than the throughput which is influenced by physical rate adaptation and the degree of aggregation, we have used the sniffer provided with *faifa* [12]. We have counted the number of frames that are either the last ones of a burst or that do not belong to a burst. This is the same methodology used in [13] to measure the number of neighbouring channel accesses between channel attempts of a target node. In this work, we measure the per-node number of channel attempts and use this value to compute the Jain's Fairness Index, which will give us a quantitative measure of traffic differentiation.

Each experiment is run for 400s and we discard the first and last 50s so that the statistics are taken during 5 minutes. Before each test, we let each station to transmit without contention during 1 minute in order to allow initial tone maps to be negotiated. Each test is repeated 10 times.

Furthermore, in order to get more insight into the transmissions on the channel for some experiments, we have also used a spectrum analyser. We use a small coil as an antenna which is placed on one of the plugs and connected to the input of the analyser (in zero span mode and centred at 15.5 MHz).

Spectrum analyser captures (not shown due to space constraints) verify that the PRSs are used as defined in Homeplug and IEEE 1901, demonstrating that the CSMA mode and the priority resolution mechanism are used by stations for channel access and priority arbitration.

B. Scenario 1: Lower-Priority Starvation

The main goal of this scenario is to evaluate whether stations with a lower priority configuration suffer starvation when there is a saturated station sending traffic at a higher priority [5]. We have considered 2 stations sending UDP traffic to a third acting as a receiver. In order to allow for saturated conditions to hold, we have set the application data rate to 1 Gbps, which is far above the maximum physical rate of 500 Mbps supported by the PLA4215 PLC devices. Significant effort has been made to ensure both stations observe similar channel conditions. In this particular setting, the Jain's Fairness Index when both stations are sending packets using CA1 is equal to 0.9936 (measured using the number of attempts per station with *faifa* as previously described), which corresponds to a total of 462320 vs. 543176 attempts per station.

We fix one of the stations at a higher priority and change the CA of the remaining one for every experiment. Fig. 2 shows the histograms of the throughput when combining 1 CA3 with lower-priority traffic (1 CA0 and 1 CA2). Observe how, as expected, independently of the lower-priority configuration, the station sending traffic at CA3 is able to obtain a high share of channel resources (in fact, close to the maximum we have

TABLE II
JAIN'S FAIRNESS INDEX FOR *Scenario 1* (COMPUTED USING CHANNEL ATTEMPTS OBTAINED WITH *faifa*)

Configuration	Value
$n_{CA3} = 1, n_{CA0} = 1$	0.518
$n_{CA3} = 1, n_{CA1} = 1$	0.523
$n_{CA3} = 1, n_{CA2} = 1$	0.535
$n_{CA2} = 1, n_{CA0} = 1$	0.505
$n_{CA2} = 1, n_{CA1} = 1$	0.503
$n_{CA1} = 1, n_{CA0} = 1$	0.506

observed when one station transmits without contention) while the lower-priority station is not effectively able to transmit.

We have also measured the Jain's Fairness Index and considered other configurations as shown in Table II (n_{CAx} denotes the number of stations transmitting at CA x). Note the values obtained are close to the minimum of 0.5, which corresponds to the unfairest possible conditions, independently of the configuration used. Thus, the first tendency observed in [5] is also found in practice. Note that the access parameters of the different CAs do not play a major role on the results shown in Table. II, which implies that the probability of an erroneous reception and thus, not having PRSs is improbable.

C. Scenario 2: Higher-Priority Contention

Here we evaluate both: *i*) the interplay between high-priority traffic and control messages and *ii*) whether increased high-priority contention releases resources to lower-priorities.

Interplay with control messages. We first evaluate the interplay between data traffic configured at different access categories and control messages. Homeplug and IEEE 1901 standards define that control information must be periodically exchanged in order to update tone map information used for dynamic channel adaptation [4], [3]. As we noted earlier, tone maps are considered outdated and discarded every 30s [3]. Furthermore, the standards define that the access priority of channel estimation frames shall be CA2. Therefore, we expect a number of CA2 messages to be transmitted every 30s by stations with data pending for transmission in order to update tone map information. We evaluate here how performance of different priority traffic is affected by this underlying procedure under high contention.

First, we evaluate the throughput of three CA1 stations contending for the channel in saturated conditions (application data rate equal to 1 Gbps and transport protocol set to UDP). Fig. 3 shows the histograms of throughput of 10 different, 5-minute-long tests. As can be observed, the histograms are concentrated around similar means. The Jain's Fairness Index computed using channel attempts with *faifa* gives us a value equal to 0.9872, which demonstrates that although certain variability is observed in throughput, we can consider the long-term attempt fairness to be close to optimal. See [14] for more insight into short-term unfairness issues inherent to PLC MAC.

Now observe in Fig. 4 the performance when three CA3 stations contend for the channel. The throughput is in this case concentrated around 4 different values (0, 50, 80 and 180

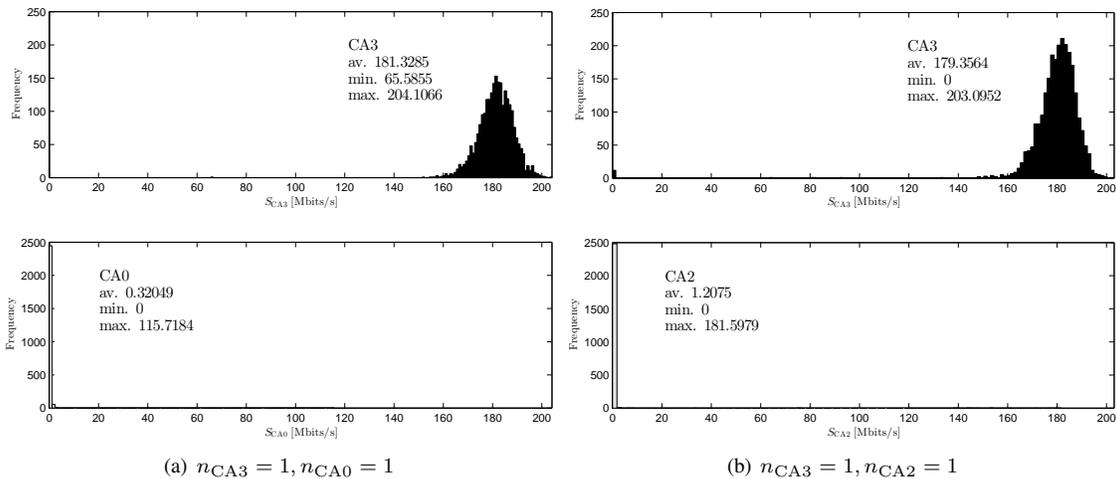


Fig. 2. Histograms of throughput (measured at 1s intervals with *iperf*) for Scenario 1.

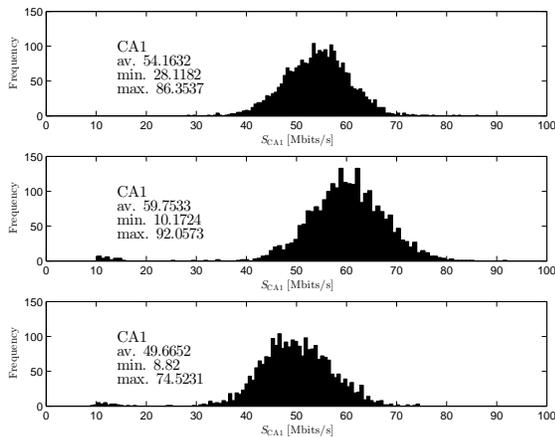


Fig. 3. Histograms of throughput (measured at 1s intervals with *iperf*) for Scenario 2 ($n_{CA1} = 3$).

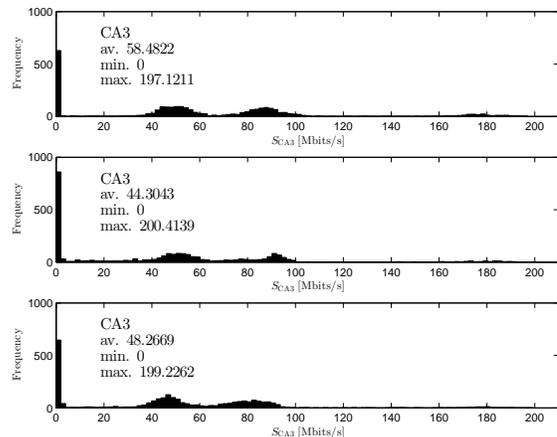


Fig. 4. Histograms of throughput (measured at 1s intervals with *iperf*) for Scenario 2 ($n_{CA3} = 3$).

Mbps). The 3 different stations follow a similar behaviour, translating into a long-term Jain’s Fairness Index equal to 0.9962. Close inspection of the temporal evolution shows that at different times some stations are not effectively accessing the channel for a considerable time interval (see Fig. 5 for a clear example). Furthermore, inspecting packet transmissions via the spectrum analyser, we can confirm that during those intervals, stations do not even notify in PRSs that they have a packet pending for transmission. Given this evidence and that the same behaviour is not found setting the access category to CA1, we believe that CA3 traffic is monopolising the channel resources and that control messages for tone map updates sent at CA2 are extremely delayed. It appears that stations have been configured to do not even attempt transmission with a stale tone map information. Therefore, throughput changes based on the number of stations effectively attempting transmission, which explains the concentration of throughput around 4 values: target station not transmitting (~ 0 Mbps), 1, 2 and 3 stations effectively contending for the channel at

approximately 50 Mbps, 80 Mbps and 180 Mbps respectively. The same behaviour, although not as severe as seen in Fig. 4, has also been obtained for CA2 (see Fig. 6 and note that relatively larger peaks are observed at 50 Mbps), which reassures us of the previously identified cause. The negative effects on user experience of this oscillating behaviour are clear, especially considering that it is found in traffic belonging to high-category configurations.

Release of resources to low priority traffic. Now, we proceed to evaluate whether an increased contention in higher-priority traffic releases resources to the lower priorities [5]. Given the previous result, we consider CA1 traffic contending with CA0 in order to avoid the issues identified relating to tone map updates. We configure 3 stations sending frames at CA1 and one CA0 station. Again, we consider saturated conditions and UDP as transport protocol.

The histograms of throughput are shown in Fig. 7. Observe how, the station sending traffic at CA0 is not able to effectively transmit. The Jain’s Fairness Index computed considering each

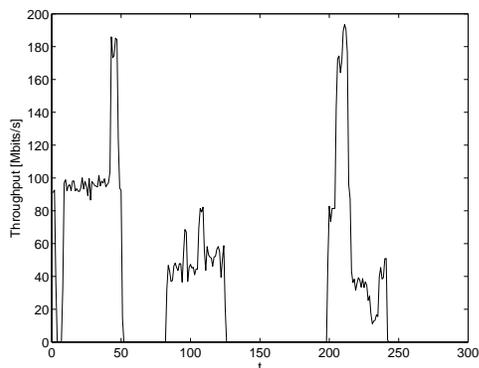


Fig. 5. Temporal evolution of throughput for a given station (measured at 1s intervals with *iperf*) for Scenario 2 ($n_{CA3} = 3$).

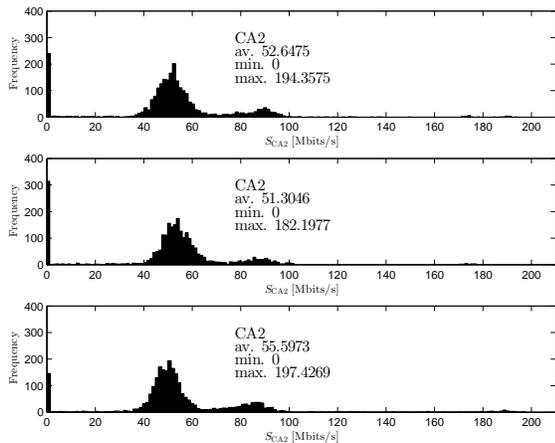


Fig. 6. Histograms of throughput (measured at 1s intervals with *iperf*) for Scenario 2 ($n_{CA2} = 3$).

of the higher-category stations using *faifa* also reports values close to 0.5, specifically: 0.5019, 0.5024 and 0.5023. These results do not seem to confirm the second tendency found in simulations [5].

In order to determine the cause of this outcome, we get further insight into the behaviour after a collision using the spectrum analyser. We have observed that after a transmission with an increased signal level, which we assume corresponds to a collision, two different behaviours occur: *i*) that there is no ACK transmission and no PRSs and *ii*) that there is a transmission of the same duration of an ACK followed by PRSs. This suggests that the receiver may be able to capture a percentage of the frames received and, therefore, PRSs may be sent even after collisions.

Thus, considering the capture effect that can occur in practice, the extent until which the channel is released to lower-priority categories is reduced and the strong starvation of lower-priorities is not necessarily ameliorated.

1) *Scenario 3: Aggregation and Buffering*: Finally, in this scenario we evaluate how vendor-specific aggregation and buffering techniques may have an impact on network performance when different priorities are considered. We have

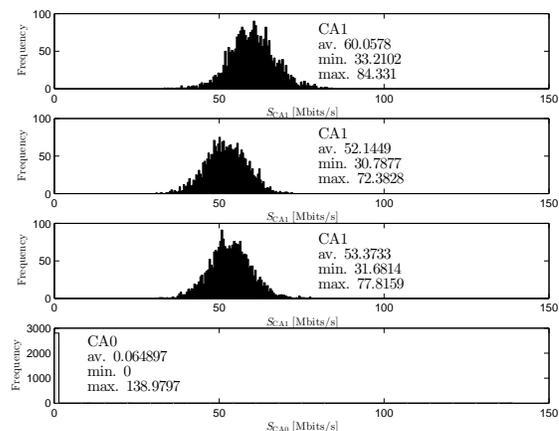


Fig. 7. Histograms of throughput (measured at 1s intervals with *iperf*) for Scenario 2 ($n_{CA1} = 3, n_{CA0} = 1$).

considered two unsaturated stations contending at different access priorities. We have set one station to transmit packets at CA3 and the other one at CA0. Two tests with data rate per station set to 120 and 160 Mbps have been performed, which correspond to different levels of nonsaturation considering the maximum throughput observed when one station transmits without contention (180 Mbps). The transport protocol used is UDP as in previous scenarios.

Results are depicted in Fig. 8. As can be observed in the histograms, while the highest-priority station faces smaller variability on its throughput, the throughput obtained by the lower-priority station varies considerably. In the 160 Mbps case (Fig. 8(a)), the throughput of the CA0 station is highly concentrated at zero but achieves non-negligible values until a maximum close to 30 Mbps. In the other case, see Fig. 8(b), we can observe how the throughput of the low-priority station substantially varies between approximately 55 and 70 Mbps. Apart from other issues which can have a big influence on short-term unfairness, such as the effect of the deferral counter and the adaptation due to varying channel conditions and estimated congestion, we have observed that changes in aggregation and buffer management have also an impact.

Inspection via the spectrum analyser reveals that the number of frames per burst and their length as well as the number of frames transmitted per time interval change for the high-priority station. Considering the traffic source is CBR, if long frames or bursts are used then the station will be left with an empty buffer with higher probability than when smaller frames/bursts are used. Thus, the lower-priority station finds different conditions for accessing the channel depending on the adaptations employed by the higher-priority station. In the short, intervals where the high-priority station is left with an empty buffer, the lower-priority station has more chances to acquire the channel, while in the cases in which smaller packets are used, the lower-priority station is not effectively able to transmit. Thus, higher-priority adaptation results in variable throughput for lower-priority stations.

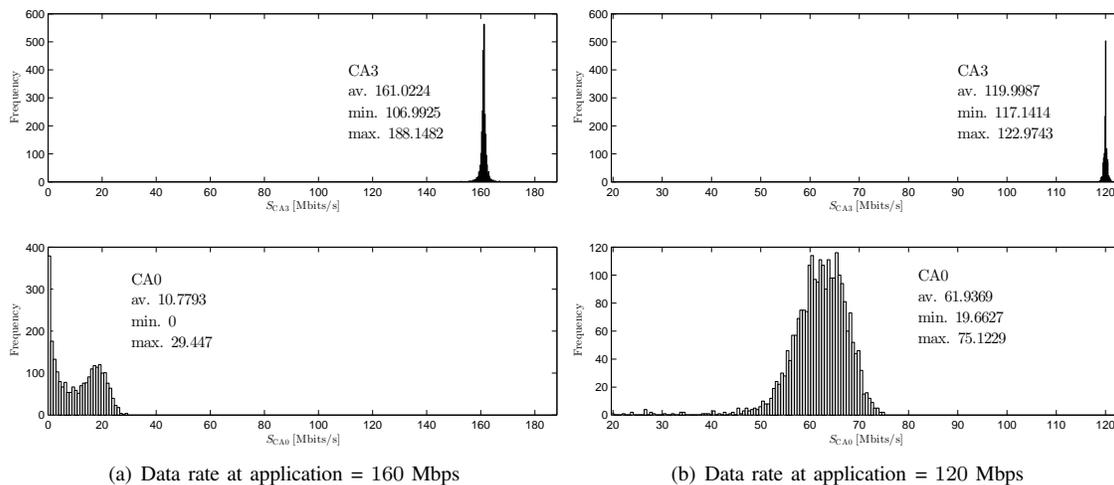


Fig. 8. Histograms of throughput (measured at 1s intervals with *iperf*) for *Scenario 3* ($n_{CA3} = 1, n_{CA0} = 1$).

V. CONCLUDING REMARKS

In this work we have identified using experimental evaluation of PLC networks a number of issues with a high impact on user satisfaction. Our outcomes also highlight the vulnerability of the technology to denial-of-service attacks. Both aspects can prevent further penetration of the technology.

An important finding of this work is the oscillatory behaviour faced by high CAs due to control messages related to tone map update sent at CA2. A stop-gap solution to this problem might be to use the previous tone map until a new one is negotiated. However, there is a simple solution to this problem: to reserve the highest priority for only sending control information and do not allow data to be sent at CA3.

The strong starvation of lower-priority flows can also have a potentially high impact on user satisfaction and is a vulnerability of the technology from the point of view of an attacker. Note that just by setting a node to continuously transmit high-priority traffic causes starvation of the other flows in the network. A solution to ameliorate this strong starvation is to limit the aggressiveness of channel attempts. Either high-priority stations can periodically refrain to signal the priority of their transmissions through PRSs or a time interval of the AC line cycle can be allocated to transmit without relying on PRSs. Alternatively, the TDMA mode defined in the standards along with an admission controller can be used to guarantee the required quality to sensitive flows without extremely penalising lower-priority traffic.

Regarding the variability of aggregation, note that further research is needed in order to adjust the level of aggregation and number of frames per burst based on the number of nodes in the network and the level of contention. An important step forward in this regard is the analysis of aggregation techniques.

We believe the contributions of this work can contribute to amending standards and allowing manufacturers design vendor-specific techniques to cope with the negative aspects of the strict prioritisation in Homeplug/IEEE 1901.

VI. ACKNOWLEDGMENTS

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