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Improving the Multiple Access Method of Home Networks over the Electrical Wiring

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Abstract Data communications on domestic low-voltage powerlines benefit from a ubiquitous and already existent infrastructure. Nevertheless, high-speed communications on this environment faces obstacles such as attenuation and noise. The HomePlug standard defines MAC- and PHY-layer protocols for home electrical wiring networks. Its MAC protocol has introduced the deferral counter (DC) mechanism, which adapts the contention of the nodes for the medium according to the network load. This article proposes the Contention window Pro-active Increase (CPI) mechanism to enhance the performance of HomePlug. The CPI mechanism is based on DC and improves the HomePlug efficiency by faster increasing the contention window size. As a consequence, there are fewer collisions and the aggregated throughput increases. Under high network load, our simulation results show a tradeoff concerning throughput and jitter. CPI improves HomePlug throughput by up to 3% with no jitter increase and by up to 15% at the cost of additional jitter.

Keywords Home networks · HomePlug · medium access control · CPI mechanism.

1 Introduction

Today, there is an increasing demand for network connectivity. Users wish to be always on-line for business or for entertainment purposes. Therefore, providing network access also at home is becoming more and more important. We define a home network as a local communication system that aims at interconnecting household appliances, sharing Internet access, and giving support to several applications. Among these applications, we have video and voice transmission, interactive games, house automation, and home health care [29].

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The different home network technologies can be classified in wired, wireless, and "no-new-wires", according to the physical medium [25]. Wired technologies need an infrastructure specifically designed for data transmission. In opposition, the wireless technology does not use wires. The most successful wired and wireless technologies today for local networks are Ethernet [13] and IEEE 802.11 [14], respectively. The upcoming "no-new-wires" technologies still use wires, but take advantage of the existent in-home infrastructure and do not require new cabling. HomePNA [2, 16, 17, 18] and HomePlug [6, 23] are two important examples. They use, respectively, the available domestic phone and electrical wiring. The "no-new-wires" solution drops down the network final cost because it avoids cabling expenses. The wireless technology, however, is another cost-effective alternative for home networking because it also reduces network infrastructure [8].

HomePNA uses phone twisted pairs, which provide lower attenuation and lower interference than ordinary electrical wires. The drawback of HomePNA is the reduced number of phone outlets in a residence, usually smaller than the number of electrical ones. From this point of view, HomePlug has ubiquity as a key advantage because electrical outlets are everywhere in a home. The problem, however, is that the electrical wiring is a hostile medium for high-speed data communications. In this case, data transmissions have to deal with high attenuation and high interference, mainly because of impedance mismatches in the electrical circuits. Therefore, transmissions on the electrical wiring have to face similar obstacles to those experienced by wireless transmissions, more specifically by IEEE 802.11 networks. Similar to IEEE 802.11, improving the network capacity is also an important issue to HomePlug. The first has been extensively analyzed in the literature (e.g. [3, 4, 5, 20, 21, 24, 27]) whereas the later is not receiving the same research effort.

Many works on HomePlug are dedicated to protocol performance analysis. Some authors compare HomePlug and IEEE 802.11 MAC protocols in terms of throughput and network connectivity (e.g. [22, 25]). Lee *et al.* [23] review in details the HomePlug standard including physical layer specification and MAC protocol operation. They present the results obtained from throughput simulations using TCP and UDP traffic for different number of nodes. Not limited to protocol performance tests, Tripathi *et al.* [28] proposed modifications to HomePlug's MAC protocol to improve data transmission performance in case of a large number of users. In their work, the contention window and the deferral counter values do not change even if a transmission fails. These values are set according to the number of contending stations instead. This approach is rather different from the original HomePlug, in which the contention window and the deferral counter values change during the network operation according to the success of each frame transmission. In the last few years, the HomePlug AV standard [1] was released. The new standard defines PHY rates up to 200 Mbps and uses a combination of TDMA (Time Division Multiple Access) and CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) access methods. TDMA guarantees limited delay for interactive applications whereas CSMA/CA fully exploits the medium capacity during data bursts. In addition, the IEEE is currently conducting a strong effort to release a new standard for broadband over power line networks. The draft standard IEEE P1901 [15] also uses a combination of CSMA/CA and TDMA medium access methods. Yoon *et al.* [30] proposed a modification to CSMA/CA access method of HomePlug AV. This modification consists of increasing the contention window size if the network is overloaded and decreasing it, otherwise. They find out through simulations that adjusting the contention window is more effective than adjusting the deferral counter. In this article, we provide an orthogonal approach to the works from Tripathi *et al.* and Yoon *et al.* to improve the performance of HomePlug 1.0.

HomePlug uses CSMA/CA, as well as IEEE 802.11, because of the high medium attenuation. Most CSMA/CA-based protocols take *reactive* countermeasures to avoid collisions. Therefore, they react after a collision has occurred to avoid further ones. In this work, we propose the Contention window Pro-active Increase (CPI) mechanism to improve the performance of the HomePlug 1.0 MAC protocol. The basic idea of using CPI is to avoid collisions by reacting *in advance*. Using CPI, a station in backoff increases its contention window size upon sensing the medium busy. This leads HomePlug to take countermeasures even before a collision happens. The CPI mechanism reduces then the collision probability resulting in better throughput. Although in this paper we focus on HomePlug 1.0, the CPI mechanism could also be added to HomePlug AV and to IEEE P1901 because both use CSMA/CA. The performance analysis of CPI is made via simulations using ns-2 [11]. Our simulation results show improvements in aggregated throughput for different packet sizes and number of nodes.

This article is organized as follows. Section 2 overviews HomePlug 1.0 MAC protocol. Section 3 is dedicated to an important characteristic of this protocol, the deferral counter mechanism. In Section 4, we introduce the CPI mechanism and derive a mathematical expression for the collision probability that indicates the CPI efficiency. Then, we analyze through simulations the HomePlug performance with and without the CPI mechanism. Section 5 concludes this article and indicates future directions.

2 Overview of HomePlug 1.0 MAC Protocol

HomePlug 1.0 uses CSMA/CA to control medium access. The electrical wiring has similar problems to the wireless medium. The high attenuation hinders the transmitter to detect an eventual collision at the destination [23, 26]. Thus, a station willing to transmit must first listen to the medium. To determine whether the medium is busy, stations use virtual carrier sense in addition to physical carrier sense. Virtual carrier sense uses information from the frame listened to assert the transmission duration and to establish a virtual allocation vector. Contending stations must wait for the expiration of their virtual allocation vectors before trying to access the medium. A data frame is considered successfully transmitted upon receipt of the corresponding acknowledgment frame (ACK).

HomePlug defines four access priority levels (Channel Access Priority - CAP) to support quality of service. These priority levels are assigned according to the type of traffic and are associated to priority classes from CA0 to CA3, where CA3 is the highest.

Stations must wait for the medium to remain idle for at least 35.84 μs, the Contention Distributed InterFrame Space (CIFS), to transmit a frame. After CIFS, stations get into the Priority Resolution (PR) phase. Two slot times, PR0 and PR1, are used to allow attempts to access the medium only from the highest priority flows, as depicted in Figure 1. Both PR0 and PR1 are equal to 35.84 μs. These two slots are used to signalize other stations a binary number which indicates the flow priority. After PR phase, stations transmitting the highest-priority flows select a random number uniformly distributed between zero and the contention window (CW) size to start a backoff counter (BC). After choosing BC, stations initialize a backoff timer (BT) to the chosen value of BC multiplied by a slot time (s):

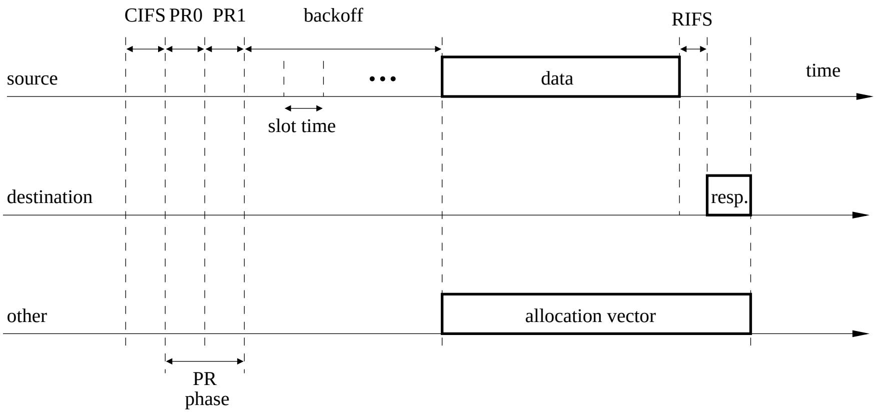

Fig. 1 Data transmission in HomePlug 1.0.

Table 1 HomePlug values for contention window (CW) size and deferral counter (DC).

BPC	CA2/CA3		CA0/CA1	
	CW	DC	CW	DC
0	7	0	7	0
1	15	1	15	1
2	15	3	31	3
>2	31	15	63	15

$$BT = BC \times s, \ where \ BC \in [0; CW].$$

The slot time is equals to 35.84 μs. As soon as stations start their backoff counter (BC), they enter into backoff phase. They wait for BC expiration to transmit their frame. The backoff counter is decremented for each slot time the medium stays idle.

The contention window (CW) size values are listed in Table 1. They are set according to the priority class of the transmitting flow. The values for CW size also depend on the backoff procedure. This procedure increases CW size and sets a variable called *Backoff Procedure Counter* (BPC), accordingly. The backoff procedure is invoked after a collision or when its probability is considerably high, estimated by HomePlug's Deferral Counter (DC). The key idea of DC is to increase the contention window size even before a collision occurrence. During the backoff phase, a contending station decrements its DC whenever another station accesses the medium first. If DC reaches zero, the collision probability is considered high and stations invoke the backoff procedure. The backoff procedure does not only increase the CW size, as mentioned before, but also the DC size. If DC is not zero, the contending stations pause their backoff counter and wait for the medium to be idle again before resuming it. The DC mechanism reduces the collision probability because stations tend to operate with higher CW sizes. When CW and DC reach the maximum values defined by the standard, they remain the same even if the backoff procedure is invoked again. The maximum values for DC and CW, when $BPC > 2$, are listed in Table 1.

During backoff, a contending station listens to the medium and sends its frame only after backoff counter expiration. As soon as the station transmits its data frame, it waits for an acknowledgment (ACK). The destination station sends an ACK after RIFS (Response InterFrame Space), if the data was correctly received. If the sending station does not receive an ACK after RIFS, it assumes that the transmission failed. Thus, it invokes the backoff procedure and waits for the medium to become idle again to retransmit. A retransmission is not required if the corresponding ACK is received. In this case, the station resets DC and CW to their minimum values.

In the next section, we investigate the DC efficiency in details.

3 Measuring the Deferral Counter Efficiency

We develop two simulation modules for ns-2.26 [11]: a propagation model for the electrical environment and the HomePlug 1.0 MAC protocol. The echo model described in [10] is used to compute the medium attenuation. This model calculates the transmission range by considering the signal transmitted a sum of different components out of phase and with different amplitudes. These different components are a consequence of the multipath transmission in the electrical wiring mainly because of ramifications and impedance mismatches.

The HomePlug module is sanity checked, as seen in Appendix A. We analytically derive a simplified expression for the HomePlug 1.0 maximum throughput and verify that the throughput obtained by the simulation module matches the one expected from the mathematical analysis.

In this section, we analyze the impact of the deferral counter on HomePlug through simulations. We choose the PHY parameters which yield the maximum throughput, as seen in Appendix A. We assume a bit error rate of 10^{-5} at the output of the decoders [12]. In addition, a receiver sends a NACK (Negative Acknowledgment) after detecting a frame with errors, causing the source to retransmit. All scenarios have a maximum of 16 transmitters. HomePlug standard states that for more than 16 nodes, the robust mode must be used. In this mode, HomePlug uses more redundancy to operate under noisy conditions, as discussed in Appendix A. Our simulation scenario uses CBR flows, with variable rates, different number of sources, and different payload sizes. All nodes are within range. We use a confidence interval of 95%.

We define the offered load as the sum of the transmission rates produced by all nodes in the network. In Figure 2, we vary the offered load keeping the number of nodes constant. The throughput achieved with DC is always higher than without it for the same number of sources. The efficiency of the deferral counter mechanism for CBR flows shows an improvement of near 9% and 32% for 2-node and 16-node transmission, respectively. The mechanism reduces the number of collisions resulting in higher throughput. Note that we plot the curve for a one-node transmission as a basis for comparison. In a one-node transmission, the throughput achieved must be the same with or without DC because there is no medium contention.

The minimum offered load which saturates the network is verified. With only one transmitter, the results with and without DC are similar because there is no medium contention. The effect of DC before saturation is worth noting (Figure 2). The throughput with DC is already higher when 2 nodes offer between 6 and 7 Mbps. Similarly, when 16 nodes produce from 4 to 5 Mbps, the throughput is already higher with DC.

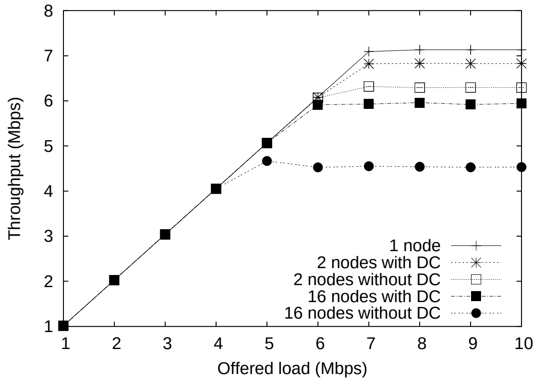

Fig. 2 Throughput of CBR flows varying the offered load.

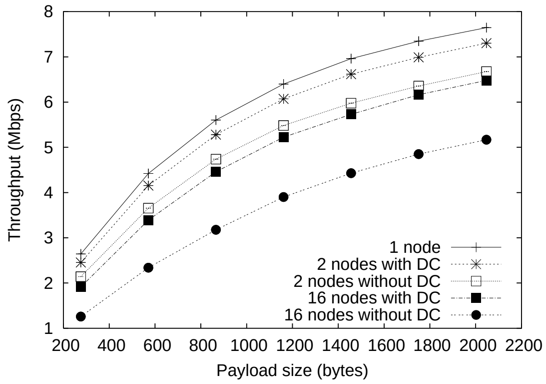

Fig. 3 Throughput of CBR flows varying the payload size.

Figure 3 plots the throughput for different payload sizes. Each node offers 14 Mbps. The throughput using small packets is lower, because of larger overhead. Additionally, the number of collisions increases with the number of nodes. As seen in Figure 3, the throughput is higher with DC independently of the number of sources and payload sizes. Moreover, the advantage of DC is proportional to the number of nodes because the collision probability grows. This suggests that the deferral counter is more effective when the network is saturated.

4 The Contention Window Pro-active Increase (CPI) Mechanism

The Contention window Pro-active Increase (CPI) mechanism is based on HomePlug's deferral counter. The goal of the proposed mechanism is to improve collision avoidance. The key difference from original HomePlug is that, using CPI, stations in backoff must *always* stop their backoff counter (BC) if they sense another ongoing transmission before their own. In a following opportunity, the deferring stations must reset their BC, increment its CW size, and choose another BC to contend for the medium. The sequence of CW sizes used is the same of the original HomePlug (Table 1). The CPI mechanism avoids more collisions by forcing stations to operate with higher CW sizes. In a few words, the operation of HomePlug using CPI is the same as using the deferral counter always equal to zero.

The backoff counter starts with a random number chosen in the interval $[0, CW]$, as seen in Section 2. Higher CW sizes produce a wider range of BC values, reducing the probability that two or more stations choose the same slot time to transmit. Hence, rapidly increasing the CW size is inversely proportional to the collision probability. On the other hand, this strategy may lead to a higher jitter as will be seen in Section 4.1. In this section, we derive an expression for the collision probability using CPI. This expression considers the following assumptions:

- stations independently choose their BC;
- the probability to choose one BC is uniformly distributed;
- different stations may have different CW sizes;
- there is no residual BC.

Taking into account the above assumptions, Expression 1 gives the probability, using CPI, that a station successfully transmits at any slot time during backoff. Let i and j be the source nodes, N the set of nodes, and n the number of nodes in the network. Additionally, let W_i and W_j denote, respectively, the number of slot times nodes i and j have in their respective contention window during backoff. The value of W_i is equal to $\mathrm{CW}_i + 1$, where CW_i represents the contention window size of node i. Therefore, node i randomly chooses one slot time out of W_i possibilities to transmit a frame. Considering that station i chooses the rth slot time in W_i, the successful transmission probability corresponds to the probability that station i chooses the rth slot time and all the other stations choose a slot time after r:

$$P_t = \frac{1}{W_i} \times \prod_{j=1, j \neq i}^{n} \frac{W_j - r}{W_j}, \ i \ and \ j \in N \mid N = \{1, ..., n\}. \quad (1)$$

If the values of W_j increase for all stations j, the probability of one transmission at the rth slot time tends to $\frac{1}{W_i}$ when $W_j \rightarrow \infty$. This result is equivalent to the probability that a station, transmitting alone, chooses any slot time to transmit among the W_i possibilities. When $W_j \rightarrow \infty$, a station j cannot choose a slot time equal to or lower than the rth slot time to transmit, thus P_t tends to the transmission of a single station. If on the other hand $W_j \rightarrow r$ then $P_t \rightarrow 0$, because all stations collide. The number of stations also influences the transmission probability. Nodes i and j compete for the medium as long as W_j is similar to W_i. When the number of nodes tends to infinity, $P_t \rightarrow 0$ because $\frac{W_j - r}{W_j} < 1$. Expression 1 is not conditional because, using CPI, contending stations always increment their CW size after sensing another ongoing transmission. Therefore, there is no residual BC.

Generalizing Expression 1, the probability of a transmission by any of the n stations during a backoff phase (Figure 1) is given by Expression 2. Note that the total successful-transmission probability must consider successful-transmission probability of every node, which are mutually exclusive events. Otherwise, a collision would happen, which contradicts our initial claim.

$$P_t = \sum_{i=1}^{n} \frac{1}{W_i} \times \prod_{j=1, j \neq i}^{n} \frac{W_j - r}{W_j}. \quad (2)$$

The rth slot time chosen for transmission must belong to the interval $[1, W_{min}]$, where

$$W_{min} = min\{W_0, ..., W_n\}.$$

This upper bound is needed because we assume that all nodes have a frame to transmit. Therefore, a transmission certainly occurs within the backoff phase of the nodes with the smallest CW size. Mathematically, considering $r \in [1, W_{min}]$, we guarantee that every multiplier in $\prod_{j=1,j\neq i}^{n} \frac{W_j - r}{W_j}$ is greater than or equal to 0. Otherwise, P_t could be negative, meaning that the medium is already occupied by another transmission.

As a transmission can occur at any slot time, we have:

$$P_t = \sum_{r=1}^{W_{min}} \sum_{i=1}^{n} \frac{1}{W_i} \times \prod_{j=1,j\neq i}^{n} \frac{W_j - r}{W_j}. \quad (3)$$

In Expression 3, if $W_j \rightarrow \infty$, then $\sum_{i=1}^{n} \frac{1}{W_i} \times \prod_{j=1,j\neq i}^{n} \frac{W_j - r}{W_j}$ tends to the one node transmission. In this case, all the terms in the sum tend to zero, except the one related to the transmission probability of station i, which tends to $\frac{1}{W_i}$. Thus, $P_t = 1$ because the transmission of this single node must happen at any slot time. Once again, note that the successful-transmission probability must consider the probability of every node successfully transmits at any slot time.

The collision probability P_c is given by Expression 4. Note that if $W_j \rightarrow \infty$, $P_t \rightarrow 1$ whereas $P_c \rightarrow 0$. Nevertheless, if the values of $W_j \rightarrow r$ or if $n \rightarrow \infty$, then $P_c \rightarrow 1$. The proposed mechanism accelerates the increase of W_j, therefore decreasing the collision probability. Expression 4 also shows that P_c is independent of the packet size, assuming that all nodes are within transmission range.

$$P_c = 1 - \sum_{r=1}^{W_{min}} \sum_{i=1}^{n} \frac{1}{W_i} \times \prod_{j=1,j\neq i}^{n} \frac{W_j - r}{W_j}. \quad (4)$$

Figure 4 illustrates the curve obtained with Expression 4 for collision probability. In this example, we assume that there is one node i using W_i=8 and the other nodes j using W_j=CW$_{max}$+1. We plot curves for different CW$_{max}$ sizes to check the influence of the W_j increase on collision probability. Note that increasing W_j, the collision probability tends to a one-node transmission as expected. The collision probability does not depend on the transmission mode used, namely normal or ROBO. Therefore, we extrapolate the number of nodes to 100.

The original HomePlug reacts slower compared to using the CPI mechanism because of the lower CW values. As a consequence, the collision probability (Expression 4) increases. On the other hand, the CW size cannot increase indefinitely because it would increase the jitter, as analyzed in Section 4.1.

4.1 Simulation results

We implement the proposed CPI mechanism in the HomePlug module described in Section 3. In the simulation scenarios the nodes transmit CBR over UDP traffic, using 1500 and 512-byte packets. Nodes are within the same transmission range, which is

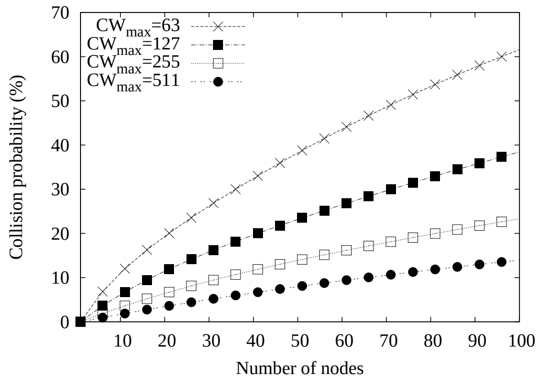

Fig. 4 Collision probability example.

computed using the echo model The bit error rate used is 10^{-5}. The number of stations in the network varies from 1 to 16 and the load generated by each station is 14 Mbps.

The behavior of the CPI mechanism is also evaluated for different maximum contention window (CW_{max}) sizes. The CW_{max} values used are 63, as defined by HomePlug 1.0, 127, 255, and 511. These results are also computed with confidence level of 95%. We assume that all nodes transmit frames using the same channel access priority, and CW size increases according to the values seen in Table 1.

Figures 5 and 6 plot the network aggregated throughput for 1500 and 512-byte packets, respectively. Results show the advantage of CPI when the network is overloaded. Using the proposed mechanism, the throughput decrease with the number of nodes becomes slower, mainly if considering larger CW_{max} sizes. This result is in accordance with Expression 3, which shows that when CW increases the network aggregated throughput tends to the throughput achieved by a single node. It is worth noting though, that the throughput gains are not proportional to the CW_{max} increase. The gains in throughput obtained increasing CW_{max} from 63 to 127 are proportionally higher than the gains obtained increasing CW_{max} from 127 to 255. The impact of using higher CW_{max} sizes is more significant when the collision probability is high. This behavior is independent of the packet size used. Depending on the number of sources and on the CW_{max} size, the throughput gain varies. For 1500-byte packets, it can reach up to 3% and 15% using CPI with $CW_{max} = 63$ and 511, respectively. An important remark is that using the same CW_{max} defined by the HomePlug standard, $CW_{max} = 63$, we already achieve gains in throughput. If not under saturated conditions, the CPI mechanism would not be so effective. In this case, a less conservative backoff procedure would be interesting.

We have also measured the average delay of the successfully transmitted frames, from its reception at the MAC sub-layer of the source to its successful reception at the destination. If a collision or a channel error occurs during the packet transmission, the additional delay for retransmission is also taken into account. We consider the propagation delay negligible.

Figures 7 and 8 plot the average delay for 1500 and 512-byte packets, respectively. The delay decreases for both packet sizes using CPI. Increasing CW faster results in fewer collisions and, consequently, fewer retransmissions. Therefore, even introducing a higher medium access time, because of the larger contention window size used, CPI

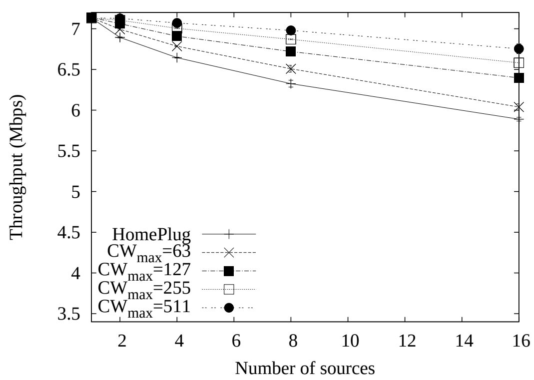

Fig. 5 1500-byte packet throughput.

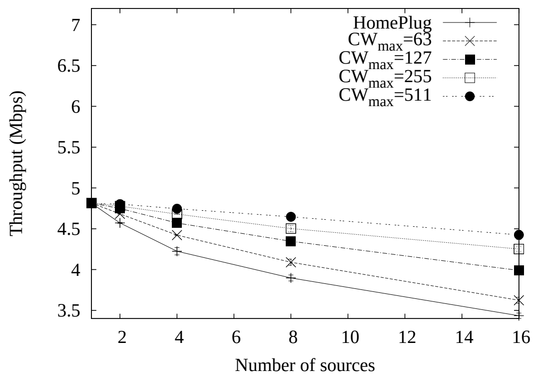

Fig. 6 512-byte packet throughput.

reduces the delay for a larger number of nodes. This is because, in average, the time needed for a retransmission is larger than the time spent to access the medium. Another important remark is that by increasing CW$_{max}$, the average delay decreases. This is because the nodes that do not access the medium increase their CW sizes faster, which reduce their probability to access the medium. Thus, the number of stations that contend for the medium is temporarily smaller – those are restricted to the stations with small CW values. Thus, as the number of nodes in conditions to access the medium is reduced, the average delay decreases. The tradeoff, as we will shortly see, is the jitter increase. If the value of CW$_{max}$ indefinitely grows, the average delay tends to the average delay of a single source, in accordance with Expressions 3 and 4.

A collision occurs whenever more than one station transmits in the same time slot. We define the collision percentage metric as the number of collisions divided by the total number of transmission attempts. Figures 9 and 10 show that transmitting at 14 Mbps, regardless the packet size, the collision percentage is equivalent. This is because the collision probability is not a function of the frame size, as seen in Expression 4. Increasing the CW size, the collision percentage decreases because the probability that at least two nodes choose the same slot time to transmit is reduced. The behavior obtained in Figures 9 and 10 follow the same behavior obtained in Figure 4.

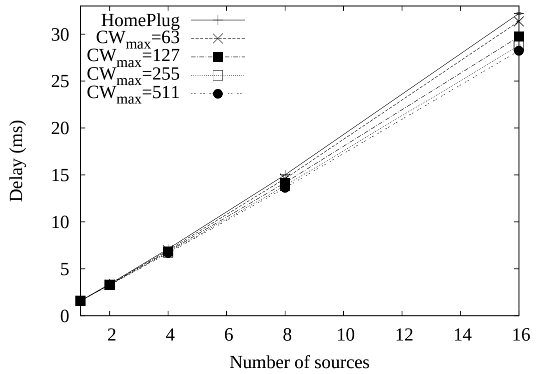

Fig. 7 1500-byte packet average delay.

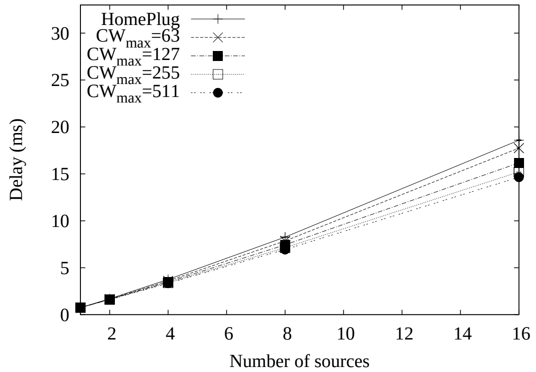

Fig. 8 512-byte packet average delay.

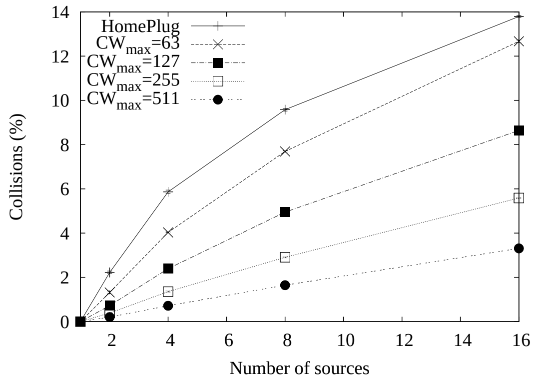

Fig. 9 1500-byte packet collision percentage.

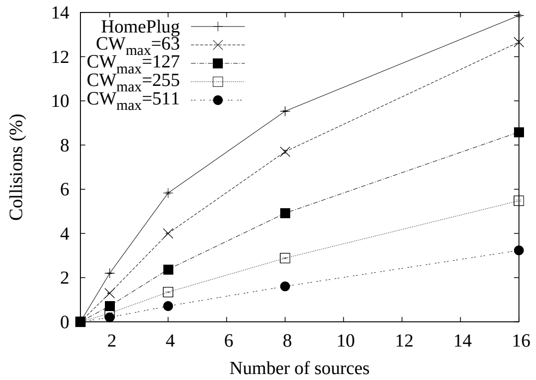

Fig. 10 512-byte packet collision percentage.

We have also analyzed the effects of CPI mechanism on jitter. In this work, we define jitter as the standard deviation of the average delay. An increase on jitter can be a consequence of: multiple retransmissions or fast CW size increase. In both cases, an increase on jitter represents a short-term unfairness in medium access. In CPI case, this is an interesting effect because CPI avoids retransmissions but at the same time increases faster the CW size. Increasing faster the CW size, the probability of successive transmissions by the same station is high because the CW value set is equal to the minimum value (CW_{min}) possible. In opposition, contending stations have their chances to access the medium reduced because choosing a backoff counter (BC) small enough becomes more difficult. Therefore, the short-term unfairness is a consequence of periods using high and low CW sizes. This phenomenon can be seen on jitter because it represents periods of high and low delay to transmit a packet.

Figures 11 and 12 plot the jitter for our simulated scenarios. The CPI mechanism with $CW_{max} = 63$ reduces the jitter compared to the standard HomePlug for higher loads, independently of the packet size. Therefore, the higher number of retransmissions influences more the jitter than the faster CW increase. Nevertheless, when $CW_{max} > 63$, HomePlug with CPI has a higher jitter. In this case, the effects of faster CW increase influences more than multiple retransmissions. Using higher CW_{max} values, nodes that do not access the medium tend to additionally postpone their transmissions. This leads to a more severe unfairness in medium access.

We observe a clear tradeoff between jitter and collision probability, or, ultimately, a tradeoff between jitter and throughput.

Figures 11 and 12 show that the jitter of the original HomePlug has the fastest increase. With more nodes, the number of collisions increases faster with original HomePlug than with HomePlug using CPI. This directly impacts on jitter, showing that even increasing faster the CW size, the use of CPI with $CW_{max} = 63$ improves the performance of HomePlug under all aspects analyzed. Besides, using $CW_{max} = 63$ is an important characteristic because we maintain the original CW_{max} size of HomePlug.

The CPI mechanism can be also introduced to other CSMA/CA-based protocols, such as IEEE 802.11, to further improve their efficiency [7].

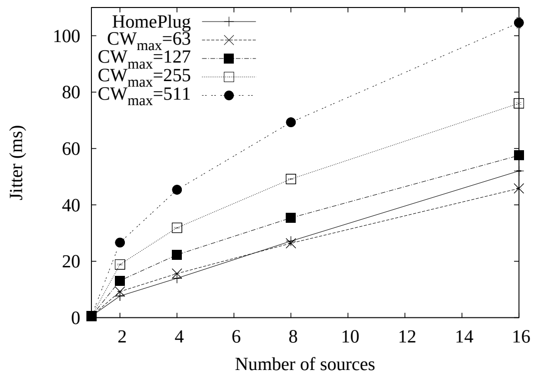

Fig. 11 1500-byte packet average jitter.

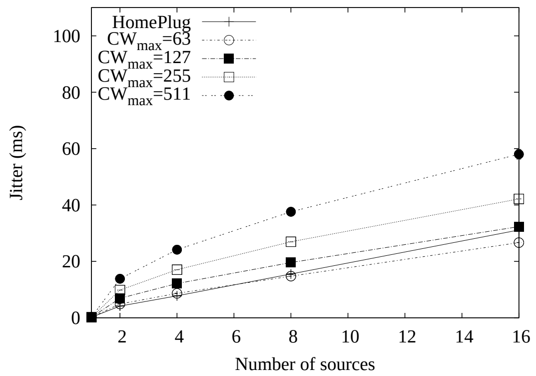

Fig. 12 512-byte packet average jitter.

5 Conclusion

HomePlug is the most used standard for data transmission over the home electrical wiring. In this article, we have proposed the Contention window Pro-active Increase (CPI) mechanism, which improves the throughput in HomePlug networks.

We have also analyzed the main characteristics of the HomePlug standard, emphasizing on its deferral counter mechanism, whose basic idea to avoid collisions is to increase the medium access average time under high network load. By analyzing HomePlug MAC, we have evaluated the DC efficiency in avoiding collisions. Using DC yields an improvement of up to 31% over DC-less HomePlug. This result has motivated the design of the CPI mechanism.

The mathematical analysis has shown that by increasing the CW_{max} values the network throughput tends to the throughput achieved by a single source node. The results obtained through simulation for the proposed mechanism are in accordance with the mathematical collision probability expression. Then, the CPI mechanism has been incorporated into the HomePlug simulation module in ns-2 [11]. Results have verified that the CPI mechanism improves the HomePlug throughput for different packet sizes and number of sources. We have also analyzed the effect of using larger values for the maximum contention window (CW_{max}) size. Varying CW_{max} from one to eight times the original $CW_{max} = 63$, defined in the HomePlug standard, improves the network throughput and reduces the average delay and number of collisions. We have verified a throughput gain of up to 15% using CPI. Nevertheless, the tradeoff is that using higher CW_{max} values also increases the jitter of the network.

The use of CPI with $CW_{max} = 63$ produces the best performance gains when taking all the aspects analyzed into account. Our future work will investigate the use of a dynamic mechanism which adapts the CW_{max} value to the network load. In addition, we plan to implement the CPI mechanism in HomePlug AV and perform measurements in a real prototype.

References

1. Kaywan H. Afkhamie, Srinivas Katar, Larry Yonge, and Richard Newman. An overview of the upcoming HomePlug AV standard. In *International Symposium on Power Line Communications and Its Applications (ISPLC)*, pages 400–404, April 2005.
2. A. Amodei Jr., L. H. M. K. Costa, and O. C. M. B. Duarte. Increasing the throughput of HomePNA. *International Journal of Communication Systems*, 21 (7):695–711, July 2008.
3. G. Bianchi. IEEE 802.11-saturation throughput analysis. *IEEE Communications Letters*, 2(12):318–320, December 1998.
4. L. Bononi, M. Conti, and L. Donatiello. Design and performance evaluation of a distributed contention control (DCC) mechanism for IEEE 802.11 wireless local area networks. In *ACM International Workshop on Wireless Mobile Multimedia (WoWMoM'98)*, pages 59–67, Dallas, USA, October 1998.
5. I. Broustis, K. Papagiannaki, S. V. Krishnamurthy, M. Faloutsos, and V. P. Mhatre. Measurement-driven guidelines for 802.11 WLAN design. *IEEE/ACM Transactions on Networking*, 18(3):722–735, June 2010.
6. Miguel Elias M. Campista, Luís Henrique M. K. Costa, and Otto Carlos M. B. Duarte. Improving the data transmission throughput over the home electrical wiring. In *IEEE Conference on Local Computer Networks (LCN'05)*, pages 318–325, Sydney, Australia, November 2005.
7. Miguel Elias M. Campista, Luís Henrique M. K. Costa, and Otto Carlos M. B. Duarte. Improving the multiple access method of CSMA/CA home networks. In *IEEE Consumer Communication and Networking Conference (CCNC'06)*, pages 645–649, Las Vegas, USA, January 2006.
8. Miguel Elias M. Campista, Igor M. Moraes, Pedro M. Esposito, Aurelio Amodei Jr., Daniel O. Cunha, Luís Henrique M. K. Costa, and Otto Carlos M. B. Duarte. The ad hoc return channel: A low-cost solution for Brazilian interactive digital TV. *IEEE Communications Magazine*, 45(1):136–143, January 2007.
9. Min Young Chung, Myoung-Hee Jung, Tae-Jin Lee, and Yutae Lee. Performance analysis of HomePlug 1.0 MAC with CSMA/CA. *IEEE Journal on Selected Areas in Communications*, 24(7):1411–1420, July 2006.
10. K. M. Dostert. Power lines as high speed data transmission channels - modelling the physical limits. In *IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA'98)*, volume 2, pages 585–589, Sun City, South Africa, September 1998.

11. K. Fall and K. Varadhan. *The ns Manual*. UC Berkeley, LBL, USC/ISI, and Xerox PARC, August 2006. Available at http://www.isi.edu/nsnam/ns/ns-documentation.html.
12. J. Foerster and J. Liebetreu. FEC performance of concatenated reed-solomon and convolutional coding with interleaving. Technical report, IEEE, June 2000. Available at http://ieee802.org/16/phy/contrib/802161pc-00_33.pdf.
13. IEEE. Carrier sense multiple access with collision detection (CSMA/CD) access method and physical layer specifications. IEEE Standard 802.3, 2002.
14. IEEE. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. IEEE Standard 802.11, 1999.
15. IEEE. Broadband over power line networks: Medium access control and physical layer specifications. IEEE P1901 Draft Standard, 2009.
16. ITU-T. G.989.1: Phoneline networking transceivers - foundation. Recommendation, February 2001.
17. ITU-T. G.989.2: Phoneline networking transceivers - payload format and link layer requirements. Recommendation, November 2001.
18. ITU-T. G.989.3: Phoneline networking transceivers - isolation function. Recommendation, March 2003.
19. M.-H. Jung, M. Y. Chung, and T.-J. Lee. MAC throughput analysis of HomePlug 1.0. *IEEE Communications Letters*, 9(2):184–186, February 2005.
20. Wen-Kuang Kuo and C.-C.J. Kuo. Enhanced backoff scheme in CSMA/CA for IEEE 802.11. In *IEEE VTC-Fall*, pages 2809–2813, Orlando, USA, October 2003.
21. Y. Kwon, Y. Fang, and H. Latchman. A novel MAC protocol with fast collision resolution for wireless LANs. In *IEEE Infocom*, pages 853–862, San Francisco, USA, March 2003.
22. M. K. Lee, H. A. Latchman, R. E. Newman, S. Katar, and L. Yonge. Field performance comparison of IEEE 802.11b and HomePlug 1.0. In *IEEE Conference on Local Computer Networks (LCN'02)*, pages 598–599, Florida, USA, November 2002.
23. M. K. Lee, R. E. Newman, H. A. Latchman, S. Katar, and L. Yonge. HomePlug 1.0 powerline communications LANs - Protocol description and performance results. *International Journal of Communication Systems*, 16(5):447–473, June 2003.
24. Jinyang Li, Charles Blake, Douglas S. J. De Couto, Hu Imm Lee, and Robert Morris. Capacity of ad hoc wireless networks. In *ACM MOBICOM*, pages 61–69, Rome, Italy, July 2001.
25. Yu-Ju Lin, Haniph A. Latchman, and Richard E. Newman. A comparative performance study of wireless and power line networks. *IEEE Communications Magazine*, 41(4):54–63, April 2003.
26. A. Papaioannou and F.-N. Pavlidou. Evaluation of power line communication equipment in home networks. *IEEE Systems Journal*, 3(3):288–294, September 2009.
27. Y. C. Tay and K. C. Chua. A capacity analysis for the IEEE 802.11 MAC protocol. *Wireless Networks*, 7(2):159–171, March 2001.
28. Kartikeya Tripathi, Jong-Dae Lee, Haniph Latchman, Janise McNair, and Srinivas Katar. Contention window based parameter selection to improve powerline MAC efficiency for large number of users. In *IEEE International Symposium on Power Line Communications and Its Applications (ISPLC'06)*, pages 189–193, Orlando, USA, March 2006.

29. Zdenka Uhríková, Chris D. Nugent, David Craig, and Václav Hlavác. Detection of aberrant behaviour in home environments from video sequence. *Annals of Telecommunications*, 65(9-10):1–11, Sep-Oct 2010.
30. Sung-Guk Yoon, Jeongkyun Yun, and Saewoong Bank. Adaptive contention window mechanism for enhancing throughput in HomePlug AV networks. In *IEEE Consumer Communication and Networking Conference (CCNC'08)*, pages 190–194, Las Vegas, USA, January 2008.

A HomePlug 1.0 Maximum Throughput

This appendix derives a simple mathematical expression for HomePlug 1.0 maximum throughput, which can be used as sanity check for our HomePlug 1.0 simulation module.

The HomePlug 1.0 standard uses the spectral band from 4.49 to 20.7 MHz. OFDM (Orthogonal Frequency Division Multiplexing) is used with 84 sub-carriers evenly spaced. Among these 84 sub-carriers, 8 can be disabled to avoid interference with amateur bands. Each OFDM symbol has a duration of 8.4 μs.

The PHY payload of HomePlug consists of a number of blocks with 20 or 40 OFDM symbols each, encoded on a link-by-link basis using Reed-Solomon and convolutional concatenated codes. The division in blocks is employed to avoid the impulsive noise that can damage symbol sequences. The damage can be more severe especially when using differential modulation because at least two symbols are lost at a time. The convolutional encoder has constraint length 7 and code rates of $\frac{1}{2}$ or $\frac{3}{4}$, selected during the channel adaptation. The Reed-Solomon code, which is used next, has coding rates ranging from $\frac{23}{39}$ to $\frac{238}{254}$.

Taking into account all the above PHY transmission parameters, the physical layer can offer up to 139 different rate combinations, ranging from 1 to 14 Mbps. Additionally, HomePlug has a especial mode, called ROBO (ROBust OFDM), which uses greater redundancy to operate under noisy conditions. The ROBO mode uses DBPSK (Differential Binary Phase Shift Keying) modulation, with a redundancy level that reduces the symbol rate to $\frac{1}{4}$ bit/symbol/sub-carrier. It also uses a Reed-Solomon code with different code rates, which range from $\frac{31}{39}$ to $\frac{43}{51}$. The ROBO mode reduces the maximum transmission rate to 0.9 Mbps.

The maximum 14-Mbps transmission rate of HomePlug 1.0 is obtained using the maximum number of sub-carriers and the parameters of error correction codes that produce the minimum redundancy. The 8 sub-carriers that can be disabled due to amateur band are also used. Hence, as the symbol rate per second is equal to $\frac{1}{8.4\mu s}$, using 84 sub-carriers, a 10^7 symbols/s rate is obtained. Using DQPSK (Differential Quadrature Phase Shift Keying) modulation, which employs 2 bits per symbol, a 20 Mbps maximum rate is reached. Nevertheless, the error correction codes use some of these bits to offer higher robustness to HomePlug. Therefore, the maximum throughput taking the error correction redundancies out is 14 Mbps, which is approximately 20 $Mbps \times \frac{3}{4} \times \frac{238}{254}$. This is not yet the effective data transmission rate since it neglects the overhead due to delimiters, interframe spaces, backoff, headers, and other required fields as seen in Figure 13.

We make the following assumptions for simplicity to compute the maximum throughput of HomePlug 1.0:

- there is one node transmitting and one node receiving;
- there is always one frame about to be transmitted;
- the bit error rate is null;
- frames are always successfully transmitted.

Figure 13 illustrates the overhead incurred in the transmission of a HomePlug frame. Expression 5 computes the HomePlug maximum throughput (R).

$$R = \frac{d}{o+t}\ Mbps, \tag{5}$$

where d is the payload size in bits, o is the overhead time in microseconds, and t the payload transmission time in microseconds. A HomePlug frame is composed of the header, the variable

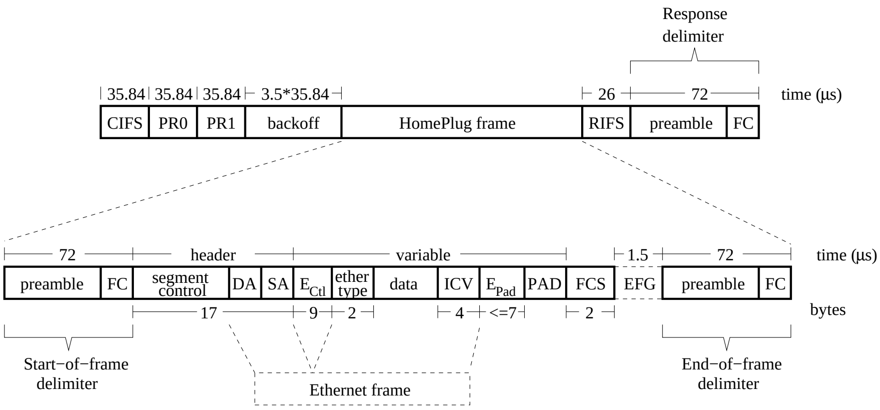

Fig. 13 Times needed for a HomePlug 1.0 frame transmission.

field, the FCS (Frame Check Sequence), the start and the end of frame delimiters, and the EFG (End-of-Frame Gap), as depicted in Figure 13. The End-of-Frame Gap is a delay allocated for the processing of the frame received. The time spent with overhead, o, is given by:

$$
\begin{aligned}
o &= (CIFS + PR0 + PR1 + \overline{backoff} + 3 \times delim. + RIFS + EFG)\ \mu s \\
o &= (35.84 + 35.84 + 35.84 + 3.5 \times 35.84 + 3 \times 72 + 26 + 1.5)\ \mu s \\
o &= 476.46\ \mu s.
\end{aligned} \tag{6}
$$

All stations must correctly receive the delimiters as well as the priority resolution signals. Therefore, they are sent using all the sub-carriers, with the same modulation and the same codification, regardless the data sender or receiver. The term $\overline{backoff}$ of Expression 6 represents the average backoff time taking into account the initial size of the contention window. Hence, $\overline{backoff} = \frac{CW_{min}}{2} \times (slot\ time) = \frac{7}{2} \times 35.84\ \mu s$ since we are assuming neither contention nor bit error rate. The header, the FCS, the encryption control (E_{Ctl}), the encryption padding (E_{Pad}), and the ICV (Integrity Check Value), which is the Ethernet FCS, are included in the data transmission time because they are sent at the same rate as the data. The HomePlug header is composed by a segment control plus the Ethernet source and destination addresses (SA and DA). The E_{Pad} is required because the encryption algorithm employed uses blocks of 8 bytes. Thus, besides the data, there is a 34-byte overhead plus the E_{Pad} added to the number of symbols to be transmitted. The number of symbols transmitted is denoted by n_s. The payload transmission time, t, is equal to the number of symbols, n_s, multiplied by the time needed to transmit one symbol, 8.4 μs.

$$t = n_s \times 8.4\ \mu s. \tag{7}$$

The value of n_s depends on the number of bits per symbol (m) which is a function of the used modulation, the number of sub-carriers (n_c), the multiplication of the two error correction code rates (c), and the number of symbols per block (n_b) as shown in Expression 8. The data is transmitted into 20- or 40-OFDM symbol transmission blocks to combat impulse noise. Thus, the block padding fills the last physical transmission block with zeros if the number of symbols of the frame is not a multiple of the used block size. Thus, in Expression 8, the number of blocks must be rounded up. Larger block sizes are more robust against noise, however, may lead to higher overhead.

$$n_s = \left\lceil \frac{1}{n_b} \times \frac{d + (34 + E_{Pad}) \times 8}{m \times n_c \times c} \right\rceil \times n_b\ symbols. \tag{8}$$

The encryption padding, E_{Pad}, is calculated as shown in Expression 9. The payload size ($d + E_{Pad}$) must be a multiple of 8 bytes. Thus,

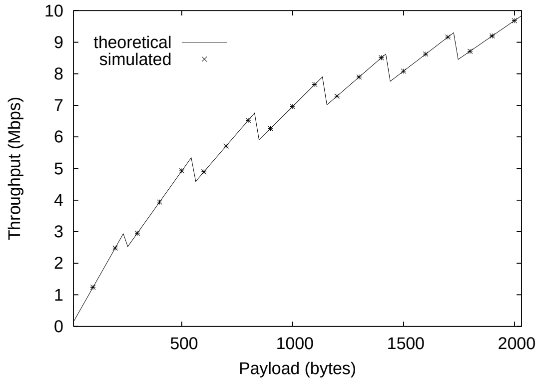

Fig. 14 Maximum throughput of the HomePlug MAC protocol.

$$E_{Pad} = \left\lceil \frac{d}{8 \times 8} \right\rceil \times 8 - \frac{d}{8} \ bytes. \tag{9}$$

Replacing 6, 7 and 8 into 5 the maximum throughput of HomePlug 1.0 is obtained:

$$R = \frac{d}{476.46 + \lceil \frac{1}{n_b} \times \frac{d+(34+E_{Pad})\times 8}{m \times n_c \times c} \rceil \times n_b \times 8.4} \ Mbps. \tag{10}$$

For the maximum throughput, $m = 2$ bits/symbol, $n_c = 84$ sub-carriers, $c = \frac{3}{4} \times \frac{238}{254}$ and $n_b = 20$ symbols per block. Figure 14 plots the maximum throughput obtained with Expression 10 for different payload sizes. In Figure 14, the full line represents the theoretical values whereas the dots are the values obtained through simulation. We observe that the simulation points match the theoretical curve.

The maximum throughput has a saw-tooth shape due to the padding inserted in the frames to keep the number of symbols per block always a multiple of 20. The periodic falls happen when another block of symbols is needed. As the payload increases, the padding decreases and the throughput grows until another block is needed.

A more precise calculation of the HomePlug maximum throughput must consider medium contention and bit error rates. This is not our purpose in this article, however, we encourage readers to take a look at [9, 19].