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Performance Evaluation under an AFR Scheme CSMA/CA for HomePlug AV Supported in Bianchi's Model

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Abstract

Background/Objectives: HPAV uses a new retransmission model of lost packages called Aggregation with Fragment Retransmission (AFR), which utilizes CSMA/CA as a mechanism to accessing the media. The main purpose of this paper is to assess the performance of a network supported in HPAV standard under the scheme AFR. **Methods/Statistical Analysis:** In this paper, the concept of saturation of throughput will be used for a finite number of stations . For that matter, it is necessary to assume that the size of the package is fixed of bits to a rate of Mbps. Additionally, an adaptation to Bianchi's model was carried out adjusted to the MAC structure of HPAV, which allows to represent CSMA/CA as a Markov's chain in discrete time of two dimensions. All this is done in order to represent the back-off procedure under a scheme DCF with saturated stations. **Relevance of the Subject:** AFR is a scheme that was proposed in order to achieve a high efficiency in the control layer of media access (MAC), based on CSMA/CA, and that, to date, has only been considered in Wireless networks supported in 802.11n. To date, similar works have not yet been found applicable to HPAV in the vast bibliographic sources. **Results:** Based on the obtained results, it was possible to observe that the model allows to assess the probability of lost packages, the MAC efficiency, the throughput and the delay levels in a PLC network, under a scheme AFR, subject to the number of stations, the size of the containment window and bandwidth available in the channel. **Application/Improvements:** It is recommended to carry out similar studies under the use of TDMA over HPAV for the voice and video broadcasting, having into account that HPAV uses a mechanism of accessing to the hybrid media in order to offer adequate levels of QoS.

Keywords: HomePlug, Performance, Powerline, Throughput, AFR, CSMA/CA

1. Introduction

Power Line Communications (PLC) refers to one group of technologies that allow to establish communication processes by means of the use of electric network as a physical means of transmission, where HomePlug AV (HPAV) is one of the standards of higher acceptance on the PLC technology[1]. HPAV uses OFDM (Orthogonal Frequency Division Multiplexing) as a multiplexing technique of information about the PLC channel. Such technique operates in the range of 1.8MHz to 28MHz, and divides the spectrum in 1055 subcarriers, from which only 917 are active for the American system, by using adaptive modulation for each subcarrier, depending on the channel conditions. The technique uses CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) and TDMA (Time Division Multiple Access) as mechanism of media accessing, where CSMA/CA is meant for the

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transmission of data packages, while TDMA is used for transmitting voice and video packages, in order to offer adequate levels of QoS. Additionally, HPAV uses a central coordinator called CCo, which is in charge of allocating resources and network accessing to PLC[2-4].

HomePlug Powerline Alliance is an association of companies related to PLC. Their members provide the capacity and the funding that is required to develop such technology. In June, 2001, the Homeplug c1.0 Standard was launched into the market; such standard allows to reach velocities up to 14 Mbps. Currently, the most recent standard is the HomePlug AV2, which allows to reach velocities up to 500 Mbps[5].

HPAV includes a new model for transmitting lost packages, or that have not been properly received, called AFR (Aggregation with Fragment Retransmission), in which the information is divided into multiple blocks (PB) of constant length (; those blocks are added and transmitted in only one frame of great length, retransmitting just those corrupted fragments that could not pass the FCS verification of the receiver[4]. One important element to consider is that the blocks will not be decoded, assembled and moved into subsequent stages until they have not been properly received; this action can cause considerable delays that may severely affect the performance of a station or a service that demands high levels of QoS[6]. For the effective recovery of a great number of block faults (PB), HPAV uses a secondary level mechanism of MAC with selective recognition SACK. Such mechanism is the one in charge of concatenating the blocks conforming each segment of MSDU.

In view of the above, the objective of this paper is to assess the performance of a PLC network on a saturation stage under a scheme AFR, having into account that on the consulted sources, there was no evidence of papers considering the proposed scheme, oriented to Power Line Communications.

2. Concept Headings

2.1 Access to the Media using CSMA/CA

The HomePlug Powerline Alliance established the use of CSMA/CA as a protocol of the MAC layer for PLC networks under the Standard HomePlug 1.0. The previous use took place as the electrical network is subject to the noise levels higher than those of the Ethernet networks. Thus, a protocol, that avoids collisions (CSMA/CA) was considered, instead of a protocol based on collision detection (CSMA/CD), which implies that each node can be heard by other nodes[7,8].

CSMA/CA is a technique of random access focused on hearing the existence of carrier waves in the media of transmission, and verifying that such media is free of such waves before sending the information through the channel[9]. CSMA/CA avoids that the transmission of various devices can be carried out in the media, at the same time; such action, although it reduces collisions, doesnot stop such collisions from happening completely[10].

The CSMA/CA used in PLC is slightly modified in comparison to the one used in Wi-Fi. It uses the value corresponding to the number of times in which a station cannot transmit, compared to other PLC stations located in the same media, under the priority established by Standard HomePlug. Such value is called DC (Deferral Counter) and increases each timea station cannot transmit, which allows to take the use of the network in accord to this priority level[11,12].

In PLC, the media is heard in both the physical layer by means of PCS (Physical Carrier Sense), and the layer of access to the level MAC by means of VCS (Virtual Carrier Sense). The PCS allows to know the state of the media by means of the presence detection of other stations PLC, and the analysis of the frames received, or by means of hearing activities in the media thanks to the Relative Power of the signal in different stations. Actually, the VCS does not allow to hear the media; however, it can be reserved exclusively for the use of PCS[8]. The VCS is maintained by the link layer and is updated based on the information contained in the delimiter. Delimiters contain information not only about the actual transmission but also about the priority of traffic that can contain the media after transmission. Information PCS and VCS is maintained by the layer MAC in order to determine the exact state of the media[3].

The media Access is controlled by means of one mechanism named IFS (InterFrame Spacing). Such space matches with the time interval between transmission of two frames. In fact, the IFS intervals are periods of inactivity in the middle of transmission used to manage the access of medium-size stations and to stablish a priority system during a transmission. The values of the different IFS will depend on the application of the physical layer. There are three types of IFS defined by the HomePlug 1.0 Standard[13,14]:

- CIFS (Contention Distributed InterFrame Spacing). The CIFS is used by the stations that wish to Access the media when it is free, which has a duration of 35,84μs.
- RIFS (Response InterFrame Spacing). It refers to the time in which a station waits for an answer from the destination station, which has a duration of 26μs before transmitting its answer. That RIFS is also used by the stations to change the delivery method to reception method.
- EIFS (Extended InterFrame Spacing). The EIFS matches with the maximum time that is needed for a station to be able to transmit. EIFS time is also used to determine how much time the media will be busy after a collision and by the process FEC (Forward Error Control), which is used to test whether there are faults/errors in received data. Time is that of 1.695μs.

For the specific case of Standard HomePlug AV, there is another group of additional IFS. In Table 1, a comparison of the IFS times is carried out, in the two most used versions of the Standard HomePlug.

Table 1. Times of IFS according to the physical layer of Standard HomePlug

	HomePlug 1.0	HomePlug AV
Time Slot	35,84 μs	35,84 μs
CIFS	35,84 μs	100 μs
RIFS	26 μs	30 a 160 μs
EIFS	1695 μs	2920 μs
AIFS		30 μs
B2BIFS		90 μs
BIFS		20 μs
RGIFS		80 μs

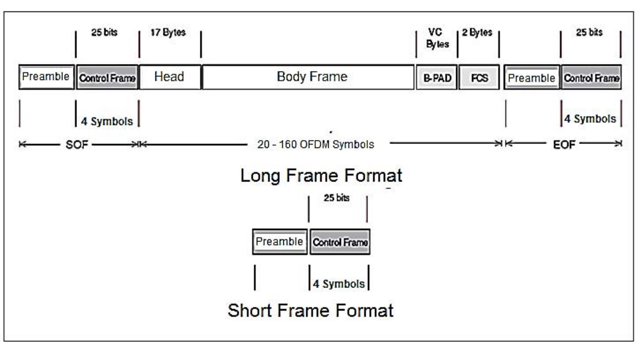

Figure 1. Formats of Basic Frame in PLC networks.

The protocol of layer MAC of PLC Works under the format of frame IEEE 802.3 with which it is possible to integrate with Ethernet. Nonetheless, some additional elements of encryption and other characteristics in the frame are included before being sent to the electrical network. PLC technology uses two formats of basic frame such as the ones showing in Figure 1. The first corresponds to a long frame, which consists on a Start of Frame delimiter (SOF), Payload (Payload) and an End of Frame delimiter (EOF, End of Frame Delimiter). The second kind corresponds to the short frame, which consists on an answer delimiter and is used as a part of the stop procedure and request ARQ (Automatic Repeat Request is expected). The ARQ is a mechanism that provides retransmission of damaged packages[11].

PLC technology limits the maximum length of the payload to 160 symbols OFDM (1.3 mseg). If the package cannot be adjusted in a long frame, a fragmenting and reassembly mechanism is used to send multiple long frames. In the frame header, all the information needed for the segmented package to be rebuilt and the payload to be protected by a FCS (Frame check sequence) should be included. Such sequence allows to detect faults in case they take place[15,16].

In HPAV, the service based on containment, consists of two periods of Access control. The first corresponds to Priority Resolution Period (PRP) followed by the Containment period. The PRP consists of two slots in charge of defining the priority resolution PRS0 and PRS1 by means of which, the MAC HPAV establish a differentiated access service with four access priorities of access to the CAP channel (Channel Access Priority) CAPx, x=0,1,2,3. The four levels of priority are allocated by the CL in which CAP3 is the highest priority and CAP0 is the lowest[17].

Table 2. Mapping between the VLAN priority and CSMA priority

Priority	Priority HomePlug AV CSMA
0 (default)	1
1	0
2	0
3	1
4	2
5	2
6	3
7	3

Table 3. Mapping between the kind of application and the user´s priority

User Priority	Type of application
7	Network Control. Requirements to maintain and support the network architecture.
6	Voice. Characterized by delays> 10ms and therefore maximum jitter.
5	Video or Audio. Characterized delays> 100ms.
4	Controlled Load. Business applications that require reservation of the bandwidth.
3	Excellent effort. «Best Effort» type services that an organization should deliver to its most important customers.
0	Best effort. LAN traffic as it is known today (this user priority is currently granted to priorities greater than 1 and 2).
1,2	Bulk transfers and other activities that are permitted on the network but should not impact the use of the network by other users and applications.

A consequence of the mapping shown in Table 2 is that the frames that carry user's default priority, have a preferential treatment compared to the prioritiesof users 1 and 2. In Table 3, the user's priorities that should be allocated to the types of applications are defined.

When the stations send their priority levels, only those with the highest priority will be authorized to Access the media during the containment period, causing the other nodes to desist and try again in the next period. In case there is multiple flows within the same station, the system of access to containment-based media should select one of the flows for this containment period. Within the frames Ethernet IEEE 802.3, there is a field used to encode VLANs according to the regulation IEEE 802.1Q. In the context of PLC networks operating in peer-to-peer mode, this field is used to label the frames according to the value of priority level established on the PRS slots. The field is composed by 3bits, from which is possible to obtain up to 8 possible values. In Table 2, the values allocated to this field according to the priority level are shown.

As fundamental part of the mechanism of priority resolution, the PRS (Priority Resolution Slot) and the signals of priority resolutions are found. After the end of each transmission, HomePlug organizes the priority resolutions in order to manage the traffic by means of two Slots of priority resolution (PRS0 y PRS1) and then a period of containment is allocated, where the approval to the node with the highest priority should take place.

2.2 Back-Off Algorithm

As mentioned before, the standard HPAV uses the CSMA/CA as one of the method of Access control to the transmission channel. When one station PLC wishes to transmit, it should waita period of time named "back-off time", whose value is allocated randomly in the interval [0, CW), where CW is defined as the containment window (CW), which corresponds to the number of slots of maximum time that a station has to wait while the media is free to begin a transmission process. The value of CW will range between the values y which are predefined by the Standard. It is important to mention that in case there are several stations wanting to carry out the transmission process, each one of them will estimate a different back-off algorithm, thus ignoring the existence of other stations from the network. If two or more stations perform the same back-off time estimation, at the moment in which the media is freed, there is the probability that such stations begin their transmission process with collisions[18]. The mathematical expression used to estimate the back-off time is (1):

$$T_{Back-off} = \text{Random}(0, CW) * \text{time slot} \tag{1}$$

Random (0, CW) is a pseudo-random value that ranges between [0, CW – 1]. Thus, the algorithm generates several time values for each station. When a station cannot successfully transmit, the value of CW will double to the point of reaching maximum value (). The expression to estimate the CW value is (1.2):

$$CW_{new} = 2 * CW_{previous} + 1 \tag{2}$$

The algorithm of back-off for HomePlug uses three counters: Back-off procedure counter (BPC), Delay counter (DC) y and Back-off counter (BC). BC corresponds to the number of time slots the containment process should wait. Such value will be allocated randomly between [0, CW]. The value of CW is defined according to the priority criteria of traffic to be transmitted (CAP) and the number of retransmissions of collisions or faults/errors during the transmission (BPC). Each station will begin its containment process for the channel when beginning to BPC in 0. Thus, the values of DC and BC depend on the value of BPC according to Table 4[7].

Table 4. CW and DC in function of BPC and CAP

BPC	CAP3 and CAP2	CAP1 and CAP0
BPC=0	CW=7 DC=0	CW=7 DC=0
BPC=1	CW=15 DC=1	CW=15 DC=1
BPC=2	CW=15 DC=3	CW=31 DC=3
BPC>2	CW=31 DC=15	CW=63 DC=15

If the media remains free during a time interval, the nodes will decrease in their BC, which will continue decreasing in 1 until reaching 0, and thus producing the transmission. Nonetheless, if the media is busy, the BC must be paused and wait until the attempt of the next transmission. Once the transmission has been completed, the transmitter waits for a selective acknowledgment of receiving (SACK) from the receiver after a defined time between frames (IFS). However, in case of not receiving the acknowledgement or SACK indication faults/errors in the transmission, the broadcast station will attempt to retransmit keeping the counters BC stopped in the rest of the stations[19].

For each retransmission attempt, the procedure uses the postponement mechanism of the counter (DC) in order to avoid collisions. The objective of such mechanism is to avoid the occurrence of collisions when the probability of happening is very high. Depending on the value of the counterDC, it should reboot. If a collision takes place or if the media is busy, both DC and BC will adopt the value of 0 (zero) and the BPC value will increase in 1. Each time the value of BPC is modified, the values of BC and DC will be rebooted.

In Figure 2, the variation in the containment window CW is shown, and the DC counter according to the number of retransmissions. Those values change from an initial value to reaching a threshold value, which generally indicates a general problem with the PLC network that wishes to broadcast[20].

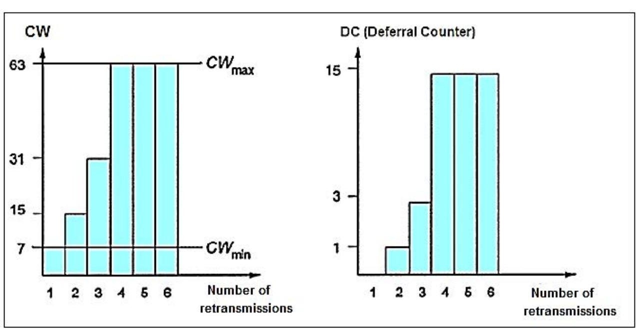

Figure 2. Size variation of the containment window according to the back-off algorithm.

A very important aspect to bear in mind in PLC networks is that the back-off algorithm can be used only when collisions do not happen. A station will increase the value of BPC (Back-Off Procedure Counter) as soon as a collision is detected or when a BPC equals 0(zero)[12].

2.3 Modelling of the Access to the Media by CSMA/CA for HPAV

In order to assess the protocol behavior, it is necessary to assume that the network is formed by an infinite number of stations, under the same mechanism of media access. In view of this, a saturation state will be considered, in which each station will always be provided with packages ready to be broadcast.

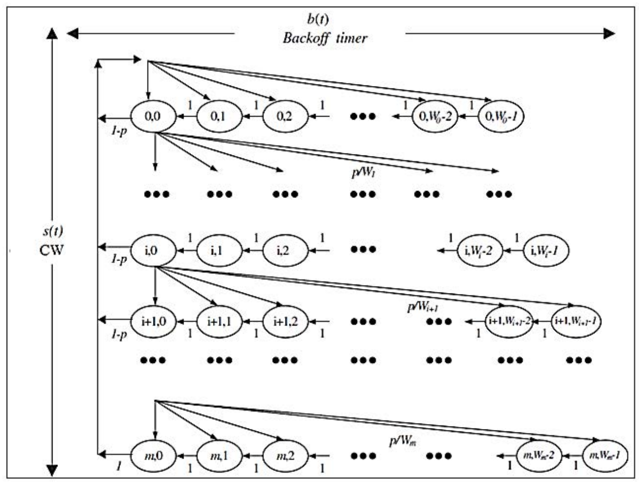

Figure 3. Markovian Bi Dimensional Model adopted for HPAV.

In order to facilitate the analysis,is defined as the collision probability of a data package, which will be considered as constant and independent from the number of collisions that such package has experienced in the past. Furthermore, The Chain model by Markov in discrete time of two dimensions, in order to represent the back-off procedure followed by each station. Bianchi is the first to introduce the stochastic process of two dimensions when modeling the behavior in back-off of a DFC scheme with saturated stations[21,22]. The process represents the back-off counter which decreases in one(1) at the beginning of each Slot. This process takes place provided the media is free. Otherwise, the counter stops. When reaches the value 0(zero), the transmission process begins and a new back-off value is allocated.

On the other hand, represents the state of back-off [0,…,m] for a station given in the instant t, when m is the limit of package retransmission and finally a discrete time scale will be adopted, where t and t+1 correspond to the beginning of two Slots of consecutive time. If the transmission is successful, the value of CW is rebooted to and the Back-off counter is allocated to a value between (0 and . If transmission fails, the value is doubled and the allocation process with the new size of the containment window is closed.

The back-off counter for each station depends on the number of collisions and successful transmissions from the past. Due to this, can be considered as a Non Markovian stochastic process. The key element to the analysis is to consider the probability of collisions constant and independent of the retransmissions number the package has suffered in the past. This assumption allows to obtain a more accurate answer as CW and n increasing[23].

In Figure 3, the bio dimensional model proposed by Bianchi is presented in order to representthe mechanism of access to the media for HPAV. In the scheme, it is possible to observe that in each state *i*, is the maximum value for the containment window, which equals for a correct transmission in the state (i,0), with a probability . In case of a collision in the state (i-1,0) a back-off value is chosen between (0, with a probability . Considering the last aspect, it is possible to represent the model as a discrete Bi-dimensional Markov chain, reason why the following notation will be adopted:

$$P\{i_1,k_1 \mid i_o,k_o\} = P\{s(t+1)=i_1, b(t+1)=k_1 \mid s(t)=i_o, b(t)=k_o\} \quad (3)$$

The transition diagram of states for this Markov chain model presents the following transition probabilities on one single step that are not null:

$$P\{i,k \mid i,k+1\} = 1 \qquad k \in [0, W_i - 2], i \in [0,m] \quad (4)$$

$$P\{o,k \mid i,0\} = (1-p)/W_o \qquad k \in [0, W_0 - 1], i \in [0, m-1] \quad (5)$$

$$P\{i,k \mid i-1,0\} = p/W_i \qquad k \in [0, W_i - 1], i \in [1,m] \quad (6)$$

$$P\{0,k \mid m,0\} = 1/W_0 \qquad k \in [0, W_i - 1] \quad (7)$$

- The equation (4) corresponds to the case in which the media is free and the back-off counter is decreased during the state *i*.
- The equation (5) represents the case in which, after a successful transmission in the state *i*, a new package begins from the state 0 and the back-off counter is selected uniformly in the interval .
- The equation (6) represents the case in which an unsuccessful transmission is produced in the state i-1, the back-off counter value increases and a new value of back-off counter, which is uniformly selected in the range
- The equation (7) represents the case in which, remaining in the state m, the containment window (CW) is rebooted to , whether because a successful transmission has taken place, or because the reattempts have reached their limit. In such last case the package is discarded and the back-off mechanism invokes a new package to be transmitted from state 0.

In order to establish a solution to the proposed Markov's chain. It is established that:

$$b_{i,k} = \lim_{t\to\infty} P\{s(t)=i, b(t)=k\} \quad (8)$$

Where, $b_{i,k}$ corresponds to the distribution in steady state of Markov's chain, with i ∈ [0,m],k ∈ [0,W_i-1], considering $b_{1,0} = p^* b_{0,0}$ y $b_{2,0} = p^* b_{1,0} = p^{2*} b_{0,0}$, it is necessary to establish the following relations for $b_{i,0}$:

$$b_{i,0} = p * b_{i-1,0} \quad ,0 < i \le m \quad (9)$$

$$b_{i,0} = p^i * b_{0,0} \quad ,0 < i \le m \quad (10)$$

The values of $b_{i,k}$ will be given by:

$$b_{i,k} = \frac{W_i - k}{W_i} * \begin{cases} (1-p) * \sum_{j=0}^{m-1} b_{j,0} + b_{m,0} & , i = 0 \\ p * b_{i-1,0} & ,0 < i \le m \end{cases} \quad (11)$$

where,

$$W_i = \begin{cases} 2^i.W & ,i \le m' \\ 2^{m'}.W & ,i > m' \end{cases} \quad (12)$$

m' = Increasing factor of CW y $2^{m'} = W_{max} = W_{m'}$. Based on the expressions (11) y (12) and considering:

$$\sum_{j=0}^{m-1} b_{j,0} = b_{0,0} * (1-p^m)/(1-p) \quad (13)$$

It is possible to obtain:

$$b_{i,k} = \frac{W_i - k}{W_i}.b_{i,0} \quad ,0 \le i \le m, 0 \le k \le W_i - 1 \quad (14)$$

Applying the condition of normalization for the proposed

$$1 = \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} \quad (15)$$

$$= \sum_{i=0}^{m} b_{i,0}\left[\frac{W_i+1}{2}\right]$$

$$= \sum_{i=0}^{m} p^i.b_{0,0}\left[\frac{W_i+1}{2}\right]$$

$$= \frac{b_{0,0}}{2}\left[\sum_{i=0}^{m} p^i.W_i + \sum_{i=0}^{m} p^i\right]$$

It is important to take into account two cases that can be represented with m y m'.

Case 1: $m > m'$ and taking as base in (12) y (15), it is possible to obtain:

$$1 = \frac{b_{0,0}}{2}\left[\sum_{i=0}^{m'}\left((2p)^i.W\right) + \sum_{i=m'+1}^{m}\left(p^i.2^{m'}.W\right) + \sum_{i=0}^{m} p^i\right]$$

$$= \frac{b_{0,0}}{2}\left[\frac{1-(2p)^{m'+1}}{1-2p}.W + 2^{m'}.W.p^{m'+1}.\frac{1-p^{m-m'}}{1-p} + \frac{1-p^{m+1}}{1-p}\right]$$

Clearing $b_{0,0}$

$$b_{0,0} = \frac{2(1-2p)(1-p)}{W.\left(1-(2p)^{m'+1}\right).(1-p)+(1-2p).\left(1-p^{m+1}\right)+2^{m'}.W.p^{m'+1}.(1-2p).\left(1-p^{m-m'}\right)}$$

Case 2: When $m \le m'$

$$1 = \frac{b_{0,0}}{2}\left[\sum_{i=0}^{m}\left((2p)^i.W\right) + \sum_{i=0}^{m} p^i\right]$$

$$= \frac{b_{0,0}}{2}\left[\frac{1-(2p)^{m+1}}{1-2p}.W + \frac{1-p^{m+1}}{1-p}\right]$$

Clearing $b_{0,0}$

$$b_{0,0} = \frac{2(1-2p)(1-p)}{W.\left(1-(2p)^{m+1}\right).(1-p)+(1-2p).\left(1-p^{m+1}\right)} \quad (16)$$

Having the former analysis into account, it is possible to estimate the probability that a station can transmit a package in a slot of time randomly selected ($\hat{o}$)[23]. It is important to have in mind that package transmission occurs when the back-off counter reaches the value 0. Based on the above, the probability τ can be estimated as follows:

$$\hat{o} = \sum_{i=0}^{m} b_{i,0} = \sum_{i=0}^{m} p^i.b_{0,0} = b_{0,0}.\frac{1-p^{m+1}}{1-p} \quad (17)$$

If considered that all stations in steady state have a probability of transmission τ, it can be said that the probability for a collision p to take place where at least one of the $N-1$ remaining stations transmit in the same slot of time, is given by:

$$p = 1-(1-\tau)^{N-1} \quad (18)$$

The equations (17) and (18) represent a non-linear system with two unknown quantities (τ y p); such system can be solved by means of the use of numerical methods, considering that τ y p can take values between $[0,1]$.

Throughput in Saturation

In this scenario, the concept of Throughput saturation will be used for a finite number N of stations[24]. For that, it will be assumed that the size of the package is fixed of L bits to a rate of Mbps. The state of saturation is defined as the limit reached by the system resulting from the fact that the input load exceeds the channel capacity[25]. In order to estimate the throughputof the system, an analysis on what happens when randomly selecting a slot of time will take place. Be P_{tr} the probability that at least one station transmits, taking into account that each station transmits with a probability τ. The expression for P_{tr} is:

$$P_{tr} = 1-(1-\tau)^N \quad (19)$$

A collision takes place when one or more stations simultaneously start a transmission process. Thus, P_s is defined as the probability that one station can successfully transmit and that the N-1 remaining stations maintain a state of listening the network. The value of P_s is given by:

$$P_s = \frac{N.\tau.(1-\tau)^{N-1}}{P_{tr}} = \frac{N.\tau.(1-\tau)^{N-1}}{1-(1-\tau)^N} \quad (20)$$

The average length of a slot of time $E[slot]$ is given by:

$$E[slot] = (1-P_{tr})\sigma + P_{tr}.P_s.T_s + P_{tr}.(1-P_s).T_c \quad (21)$$

where:

σ : Duration of a slot of empty time in conditions of free channel

T_s : Time that lasts a successful transmission

T_c : Time that lasts a collision on being detected

$1-P_{tr}$: Probability that a slot of time goes by or in state of free channel.

$P_{tr}.P_s$: Probability of having a successful transmission

$P_{tr}.(1-P_s)$: Probability of having a collision

An aspect to highlight, is that the time interval between two consecutive slots for a station can be much larger that time σ, which corresponds to the size of slots of time in counting normal conditions (for the case of HPAV $\sigma = 35.84\mu s$), due to the fact that a transmission process could be presented by other station, leading to the counter of back-off to stop when the media is busy and it is resumed when the media is free. The throughput of the system S can be expressed when dividing the load successfully transmitted in a slot of time with the average length of a slot of time.

$$S = \frac{P_{tr}.P_s.L}{(1-P_{tr})\sigma + P_{tr}.P_s.T_s + P_{tr}.(1-P_s).T_c} \quad (22)$$

Taking into account the frame structure represented in Figures 4 and 5, the values of $T_c y T_S$ depend on the mechanism of media access and can be defined as follows:

$$T_s = PRS0 + PRS1 + T_{Backoff} + T_{Header} + \frac{E[L_{pld}]}{C} + RIFS + T_{res} + CIFS \quad (23)$$

$$T_c = PRS0 + PRS1 + +T_{Backoff} + T_{Header} + \frac{E[L_{pld}]}{C} + CIFS \quad (24)$$

Where C is the bit-rate, $E[L_{pld}]$ is the avergae size off the package, $T_{Header} y T_{res}$ are the times required to transmit the package header of payload and the acknowledgement of receipt, respectively.

$$T_{Header} = \frac{MAC_{HDR}}{C} + \frac{PHY_{HDR}}{C_{Control}} \quad (25)$$

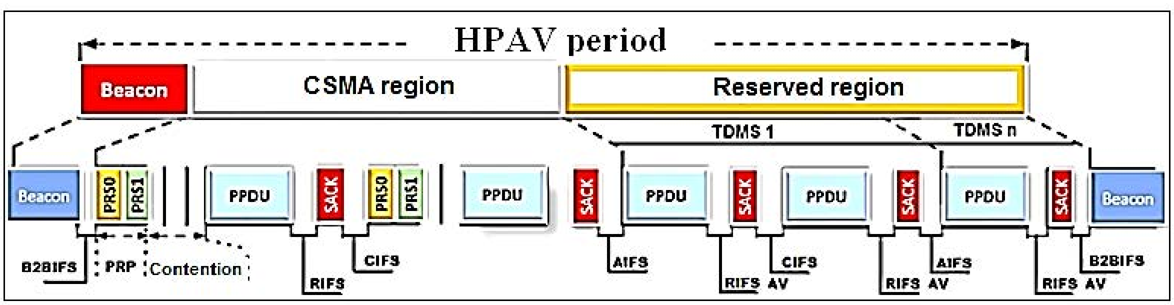

Figure 4. Structure of Frame of a HPAV period.

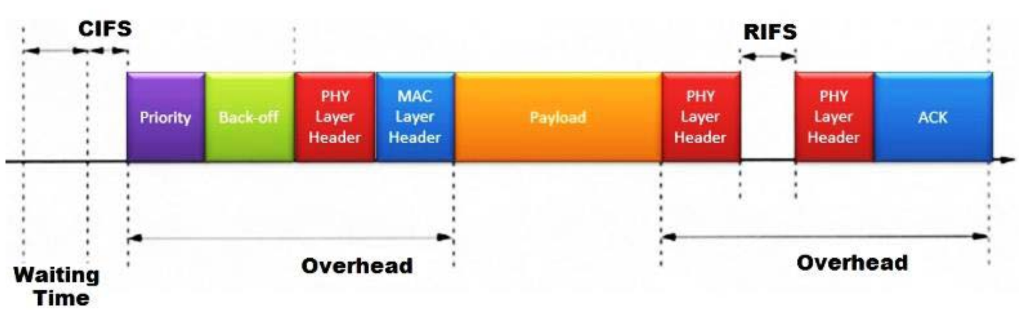

Figure 5. Maximum overload when data on HPAV in region CSMA is transmitted.

$$T_{Ack} = \frac{L_{Ack}}{C_{Control}} \approx T_{res} \qquad (26).$$

$MAC_{HDR} y PHY_{HDR}$ correspond to the MAC and the physical header (bits) respectively. $C_{Control}$ is the rate to which the bits of control are transmitted and L_{Ack} is the length of acknowledgment of receipt.

In Figure 6, it can be observed that each MAframe streamor HPAV is divided into blocks of 512 bytes. Those blocks are encrypted and encapsulated in blocks PHY_PB of 520 bytes, according to the structure represented in Figure 7. These PHY_PB are latter packaged on a MPDU (MAC Protocol Data Unit) and sent to a physical layer for their transmission. The receiver finally rebuilds the MSDU (MAC Service Data Unit), selectively acknowledging the PHY_PB. When all the PHY_PB confirming a MSDU have been correctly received, the segments are decrypted, continuing with the transit to superior layers[26,27].

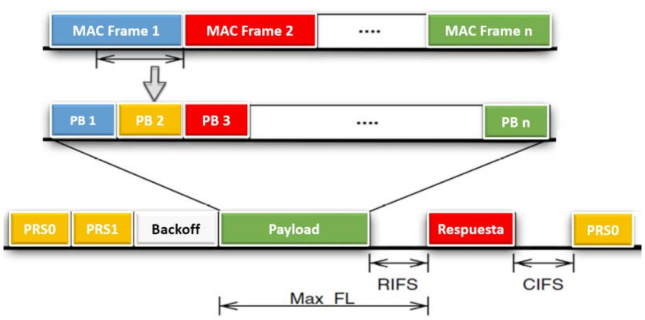

Figure 6. Sequence of timing for the transmission of MAC frames.

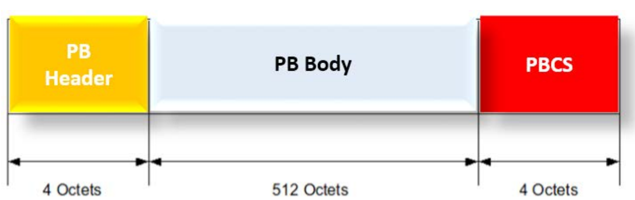

Figure 7. Block structure (PHY_PB).

In order to estimate the value of $E\left[L_{pld}\right]$ it is necessary to take into account that the maximum time of payload transmission on a frame over HPAV (Max_FL) cannot be higher than 2501.12µs, including RIFS. Thus, the maximum number of bits transmitted by a station will depend on the PHY-rate. Additionally, the quantity of bits has to be multiple of the size of PHY_PB block, adopted by HPAV as an information encapsulating mechanism (PBsize)[28]. In Table 5, the value of the most important parameters part of the HPAV standard technical specifications is summarized.

In (27) the expression to estimate the value $E\left[L_{pld}\right]$. is presented:

$$E\left[L_{pld}\right] = \frac{1}{N}\sum_{i=1}^{N} L_i = \frac{1}{N}\sum_{i=1}^{N} \frac{C_i\left(Max\_FL - RIFS\right)}{PBsize}.PBsize \qquad (27)$$

Where L_i is the number of bits that a station i transmits every time such station has access to the media, N is the number of stations in containment, C_i is the Y-rate of the station i and PB size corresponds to the block size.

Table 5. Parameters for the Home Plug AV specifications

Parameter	Value	Parameter	Value
Max_FL	2501,12 µs	Head Time HPAV	110,48 µs
Response time (T_{res})	140,48 µs	Frame Head	26 bytes
RIFS Default	100 µs	Slot time (σ)	35,84 µs
RIFS_AV	30 - 160 µs	B2BIFS	90 µs
CIFS	100 µs	BIFS	20 µs
PRS0,PRS1	35,84 µs	EIFS_AV	2920,64 µs
PB Payload (PB_{pld})	512 bytes	PBsize	520 bytes
PB Head	8 bytes		

As mentioned before, HPAV includes a new model to transmit the lost packages or those that are accurately received, named AFR. The value of Throughput in saturation state for a scheme AFR is given by:

$$S_{AFR} = \frac{P_{tr}.P_s.E\left[L\right]}{\left(1-P_{tr}\right)\sigma + P_{tr}.P_s.T_s + P_{tr}.\left(1-P_s\right).T_c} \qquad (28)$$

In (28) $E\left[L\right]$ does not represent the size of useful charge. Instead, it represents the number of bits expected to be successfully retransmitted. It is important to take into account that the scheme AFR allows the successful transmission of fragments to be received and, even if some frame fragments are damaged. In order to estimate the value of $E\left[L\right]$ the process is as follows:

Be i the number of erroneous fragments and m the number of fragments in the frame. Assuming independence and uniform distribution of the errors, it can be obtained that:

$$E[L]=\sum_{i=0}^{m}\binom{m}{i}\left(P_e^{frag}\right)^i\left(1-P_e^{frag}\right)^{m-i}\left[E\left[L_{pld}\right]-\left(i.PB_{pld}\right)\right] \quad (29)$$

with

$$P_e^{frag}=1-\left(1-P_b\right)^{PB_{pld}+PB_{FCS}} \quad (30)$$

Where P_e^{frag}, $P_b, PB_{pld}, E\left[L_{pld}\right]$ and PB_{FCS} corresponds to the probability of error in the fragment or block, the BER, the length of the fragment or block (512 bytes), the average length of payload and the length of FCS of the block (4 bytes for the case of HPAV) respectively. Solving the expression for $E\left[L\right]$, the result is:

$$E\left[L\right]=E\left[L_{pld}\right](1-P_e^{frag}) \quad (31)$$

Replacing the value of $E\left[L\right]$ in S_{AFR}, the result is:

$$_{AFR} \quad \frac{P_{tr}.P_s.E\left[L_{pld}\right](1 \quad P_e^{frag})}{\left(1-P_{tr}\right) \quad +P_{tr}.P_s.T_s+P_{tr}.\left(1-P_s\right).T_c} \quad (32)$$

Be P_{Drop} the probability of package loss in function to the number or stations that are part of the network, can be estimated as follows:

$$P_{Drop}=1-\left(1-\tau\right)^{N-1} \quad (33)$$

Probability of Discarded Packages

This is the probability in which a package is discarded by a station k andit is presented when the limit of attempts is reached. Consequently, this value of probability is independent of the mechanism of media access used.

$$P_{Drop}^{k}=p^{m+1} \quad (34)$$

A package is discarded when it reaches the last state of back-off or it experiences some other collision. The average value of slots that the station will use in the state i (including in the slot of transmission) is given by:

$$d_i=\frac{W_i+1}{2}\ ,\ i\in\left[0,m\right] \quad (35)$$

The average number of slots of s $E\left[T_{Drop}\right]$ required for a package to experience $m+1$ collisions in the $\left(0,1,2,\ldots,m\right)$ states is given by:

$$E\left[T_{Drop}\right]=\sum_{i=1}^{m}d_i$$

$$=\begin{cases}\dfrac{W\left(2^{m+1}-1\right)+\left(m+1\right)}{2} & ,m\le m' \\ \dfrac{W\left(2^{m'+1}-1\right)+\left(m+1\right)+W.2^{m'+1}\left(m-m'\right)}{2} & ,m>m'\end{cases} \quad (36)$$

Finally, the average time for a package to be discarded $E\left[D_{Drop}\right]$ is:

$$E\left[D_{Drop}\right]=E\left[T_{Drop}\right].E\left[Slot\right] \quad (37)$$

Average Delay of Packages

It is considered D the delay required for the successful transmission of a package and it is defined as the time since the package enters to the tail, until the receipt of acknowledge for this package. In case that some package is discarded, the delay time will not be included in the estimation, as such package is not properly received.

$$E\left[D\right]=E\left[X\right].E\left[Slot\right] \quad (38)$$

Where $E\left[X\right]$ corresponds to the average number of slots of time required to transmit a package successfully. $E\left[X\right]$ can be estimated by multiplying the value of d_i por la probabilidad q_i in which such package reaching the i will not be discarded.

$$E\left[X\right]=\sum_{i=0}^{m}d_i.\,q_i \quad (39)$$

The probability q_i in which a package reaches the state i of back-off and such package is not discarded, can be estimated by means of the use of (40):

$$q_i = \frac{p^i - p^{m+1}}{1 - p^{m+1}} \quad , \; i \in [0, m] \qquad (40)$$

Where p^i is the probability that one package reaches the state *i*. The expressions corresponding to p^{m+1} y $(1 - p^{m+1})$ are the result of the probabilities that a package can be discarded or not. Combining the equations (28), (39) and (40), the value of $E[X]$ is given by (41):

$$E[X] = \sum_{i=0}^{m} \left[\frac{(p^i - p^{m+1}).(W_i + 1)}{2.(1 - p^{m+1})} \right] \qquad (41)$$

Solving (41) it can be obtained that,

For $m \le m'$

$$E[X] = \frac{W\left(1-(2p)^{m+1}\right)(1-p)+(1-2p)\left(1-p^{m+1}\right)}{2(1-2p)(1-p)\left(1-p^{m+1}\right)} - \frac{p^{m+1}E\left[T_{Drop}\right]}{1-p^{m+1}} \qquad (42)$$

For $m > m'$

$$E[X] = \frac{W\left(1-(2p)^{m+1}\right)(1-p)+(1-2p)\left(1-p^{m+1}\right)+W.2^{m'}.p^{m'+1}.\left(1-p^{m-m'}\right)(1-2p)}{2(1-2p)(1-p)\left(1-p^{m+1}\right)} - \frac{p^{m+1}E\left[T_{Drop}\right]}{1-p^{m+1}} \qquad (43)$$

Replacing the value of $E[X]$, $E\left[T_{Drop}\right] and E[Slot]$ in the equation (28), the value of $E[D]$ can be estimated easily.

The process of transmitting a frame will inevitably attract an overload, reason for which is important to consider a time T_{oh}^{p}. In the model DCF, the overload includes the time T_{Header} required to transmit the header, the time T_{PRS} for the transmission of the priority header (PRS0 y PRS1), the time of Back-off $T_{Backoff}$ and the T_{Ack} for transmitting a MAC ACK. Considering the above, it is possible to define the efficiency of the MAC Throughput as:

$$\varsigma_{MAC} = \frac{T_p}{T_p + T_{oh}^{p}} \qquad (44)$$

Where:

$$T_{oh}^{p} = T_{Header} + T_{PRS} + T_{Backoff} + T_{Ack} \qquad (45)$$

$$T_p = E\frac{\left[L_{pld}\right]}{C} \qquad (46)$$

T_p is the time required to physically transmit a package (frame payload), is the rate (PHY rate) and $E\left[L_{pld}\right]$ is the size of payload.

3. Results

Here under, the results obtained during the process of simulation are presented. Such results are supported in the model proposed under a scheme of frame AFR.

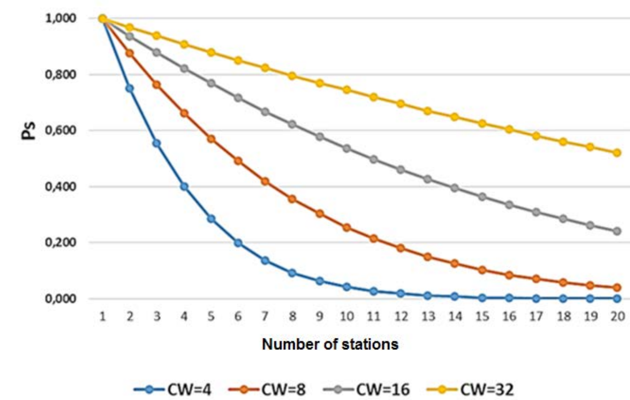

Figure 8. Probability of successfully transmitting Vs number of stations and CW.

In Figure 8, it can be observed that the probability of successfully transmitting a frame, will considerably decrease as the number of stations part of the PLC network increase. Nonetheless, its value can improve in connection with the size of the containment window.

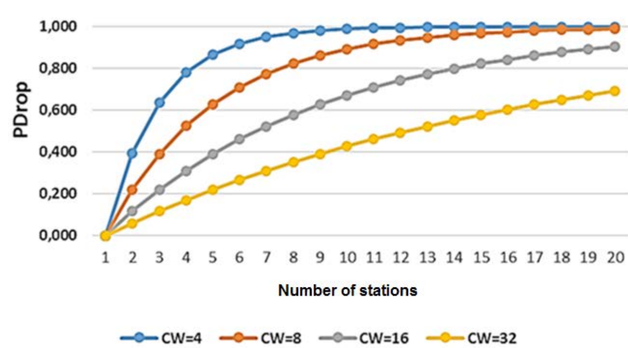

Figure 9. Probability of package loss Vs Number of stations and CW.

In Figure 9, it is possible to observe that the number of stations and the size of the containment window are parameters that have a great effect on the probability of loss packages in a PLC network, under CSMA/CA as a mechanism of media access.

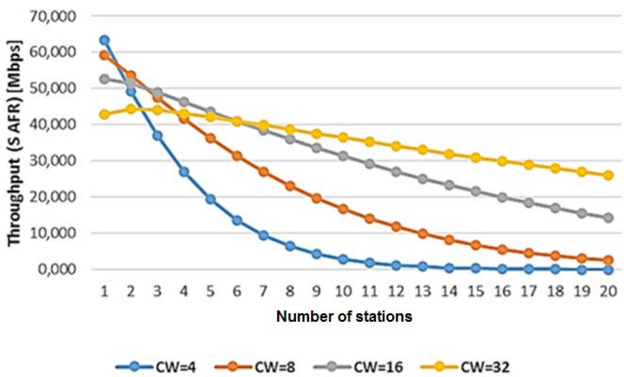

Figure 10. Throughput in Saturation (S_AFR) Vs Number of Stations and CW.

In Figure 10, it can be observed that the value of the throughput under a scheme AFR in a PLC network, depends as well, of the former parameter a great deal in function of the number of stations and the size of the containment window. However, it is possible to observe that the changes of stations are lower than 5. Such aspect can be considered as very remarkable when one wishes to implement networks of reduced size, as in residential environments.

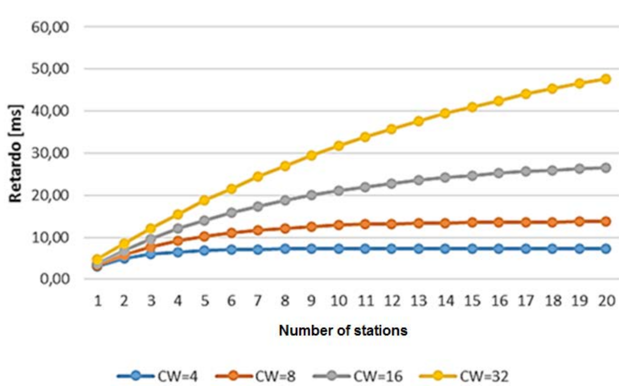

Figure 11. Delay Vs Number of Stations and CW.

In Figure 11, it can be observed that the delay increases a great deal inasmuch as the size of the containment window increases, which is coherent with the proposed model. On the other hand, it is visible that, although the number of stations part of the PLC network increases, its influence in the levels old delay is not as visible. Such aspect can be considered of great importance when comes to assessing the network performance.

In Figure 12, it is possible to observe the level of influence that the number of stations exercises and the BER on the throughput in a PLC network, where one can see that the last parameter can get to affect a great deal in as much as its value increases. In[29], it is stated that HPAV can offer appropriate levels of throughput under a $\mathrm{BER}=10^{-3}$, due to the use of a AFR scheme. However, this aspect can be refuted based on the obtained results, as it is possible to observe a fairly considerable mitigation in the throughput when considering a $\mathrm{BER}=10^{-3}$.

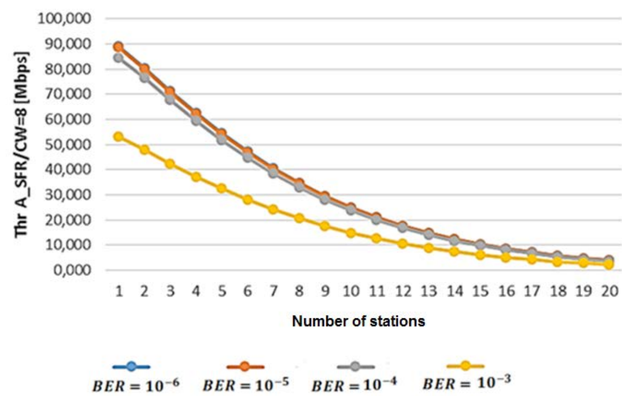

Figure 12. Throughput S_AFR Vs Number of Stations and BER.

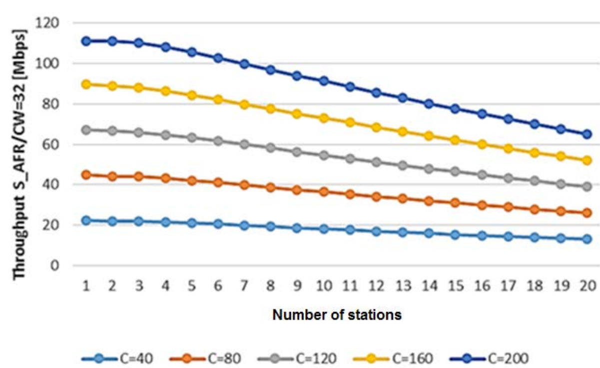

Figure 13. Throughput S_AFR Vs PHY_Rate with CW=32.

In Figure 13, the behavior shown by the Throughput in relation to the number of stations and cannel PLC capacity is presented. There, it is possible to see that the value of throughput is directly proportional to the capacity of the cannel and inversely proportional to the number of stations, which is coherent in other types of networks.

In Figure 14, it is seen that the efficiency average MAC for HPVA under CSMA/CA decreases inasmuch as the containment value increases, presenting maximum and minimum values of 80, 71% and 47, 7% respectively. This phenomenon is very important when comes to carrying out process of network optimizations, due to the fact that, according to the obtained results, considering a reduced size of window can greatly improve the efficiency of such process.

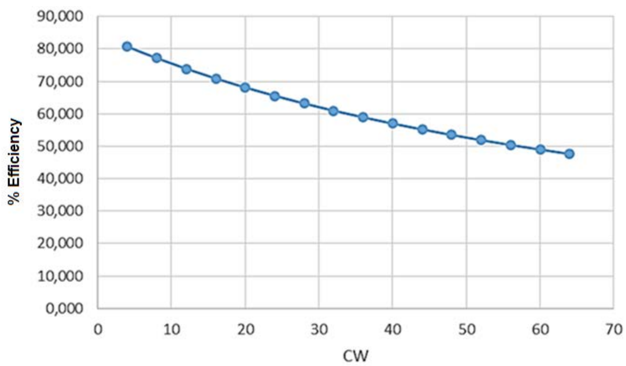

Figure 14. Efficiency average MAC for HPAV under CSMA/CA Vs CW.

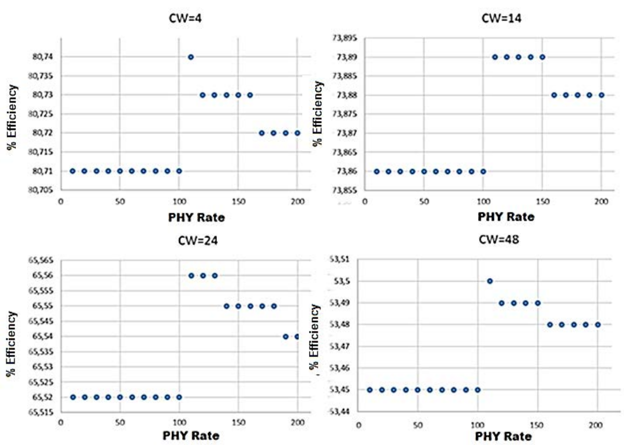

Figure 15. Efficiency average MAC Vs Capacity of cannel and CW.

Finally, in Figure 15, the relation between capacity of cannel PLC and the containment value in function of the efficiency average MAC under CSMA/CA is presented. There, it can be possible to observe a stable behavior in different frequency ranges, except when the capacity of the channel reaches a value of 110Mbps, where an abrupt change in the efficiency MAC is presented. This phenomenon is common for the four proposed containment values, which may suggest future studies on the reasons why this particular phenomenon takes place.

4. Conclusions

An important element in the proposed model, was the inclusion of the scheme named Aggregation with Fragment Retransmission, in which the information is divided in multiple blocks (PB) of constant length (PB_{size}), for its later transmission of an only frame of great length, retransmitting only the corrupted fragments that could not get to be approved by the receiver. Such scheme that, up to date, had not been considered in none of the proposed models for HPAV by other authors, allowing to represent precisely the behavior of the PLC technology. According to the results obtained, it could be observed that the model allows to properly analyze the performance of a network, in which it can be observed that the number of stations, the size of the containment window, and the channel bandwidth, are parameters that affect greatly the values related to the probability pf loss packages, the efficiency MAC, the throughput and the levels of delay in a PLC network.

5. References

1. Kalilulah SI, Rabi BJ, Chouhan K. Collisionless Data Transmission to Improve Throughput Using Additive Links On-line Hawaii Area Technique With Timeslot Communication. Indian Journal of Science and Technology. 2016 Sep 29; 9(36):1-8.
2. Anatory JN, Theethayi. Broadband Power-Line Communication Systems: Theory and Applications. 1a ed. Southampton, England: WIT Press. 2010; p. 192. Crossref.
3. El Fawal, Le Boudec J. Coexistence of Multiple HomePlug AV Logical Networks: A Measurement Based Study. 2011 IEEE Global Telecommunications Conference - GLOBECOM 2011. 2011; p. 1-5.
4. Banarwal S, Sharma A, Virdi SK, Verma H, Verma G. Power Line Communication. Indian Journal of Science and Technology. 2016 Jun; 139(21). Crossref.
5. Carcelle X. Powerline communications in practice, 1a ed. Londres, Inglaterra: Artech House. 2006; p. 370.
6. Pinero-Escuer PJ, Malgosa-Sanahuja J, Manzanares-Lopez P, Munoz-Gea JP. Homeplug-AV CSMA/CA Cross-Layer Extension for QoS Improvement of Multimedia Services. IEEE Communications Letters. 2014; 18(4):704-7. Crossref.
7. Fox-Penner P. Smart Power: Climate Change, the Smart Grid, and the Future of Electric Utilities. Island Press. 2009; p. 183-4.

8. IEEE, IEEE Communications Society. [Online]. Available from: http://www.comsoc.org/. Date Accessed: 13/09/2013.
9. Ramya R, Saravanakumar G, Ravi S. MAC Protocols for Wireless Sensor Networks. Indian Journal of Science and Technology. 2015 Dec; 8(34):1-6. Crossref.
10. IEEE, 1901-2010 - IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications. 2010.
11. Agudelo LL, Florez OA. Evaluacion de desempe-o de las tecnologias Power Line Carrier (PLC) y Wireless LAN para la implementacion al prototipo de sistema metropolitano de telemetria para la monitorizacion de parametros electricos en las redes de Distribucion de Media y Baja tens. Universidad Industrial de Santander. 2010.
12. Neill BO. A problem of rights arbitration from the Talmud. Mathematical Social Sciences. 1982; 2(4):345-71. Crossref.
13. Ekanayake J, Liyanage K. Smart Grid Technology and Applications. Wiley. 2012; p. 320. Crossref.
14. Altolini D, Benvenuto N, Pupolin S, Riva R. Preamble-based channel estimation in HomePlug AV systems. 2012 IEEE International Symposium on Power Line Communications and its Applications. 2012; p. 176-81.
15. Guillen EP, Lopez JJ, Barahona CY. Throughput Analysis over Power Line Communication Channel in an Electric Noisy Scenario. Proceedings of World Academy of Science, Engineering and Technology. 2008; p. 1-7.
16. Zimmermann M, Dostert K. Analysis and modeling of impulsive noise in broad-band powerline communications. IEEE Transactions on Electromagnetic Compatibility. 2002; 44(1):249-58. Crossref.
17. Homeplug Powerline Alliance, HomePlug AV White Paper. 2005; p. 1-11.
18. Jensen B, Slavensky H, Kjaersgaard S. Benchmarking and QoS of In-House Powerline Equipment for AV Streaming Applications. 2006 IEEE International Symposium on Power Line Communications and its Applications. 2006; p. 160-5.
19. Yoon SG, Yun J, Bahk S. Adaptive Contention Window Mechanism for Enhancing Throughput in HomePlug AV Networks. 5th IEEE, Consumer Communications and Networking Conference 2008, CCNC 2008. 2008; p. 190-4.
20. Andreou GT, Dimoulkas IG, Mazneikou MI, Papadopoulos TA, Labridis DP. Performance of Commercially Available Residential PLC Modems. 2007 IEEE International Symposium on Power Line Communications and Its Applications. 2007; p. 116-20. Crossref. PMid:17684589.
21. Lee Y, Latchman HA, Ha H, Hwang M. QoS augmented CSMA/CA MAC protocol for high speed multimedia powerline communications. 2012 IEEE International Symposium on Power Line Communications and Its Applications. 2012; p. 236-41.
22. Granados AG, Vesga FJC. Analisis sobre el comportamiento del Throughput en redes LAN bajo tecnologia Power Line Communications. Revista Iteckne - UNIVERSIDAD SANTO TOMaS. 2012; 9(2):22-32.
23. Katar S, Mashburn B, Newman R, Latchman H. Allocation Requirements for Supporting Latency Bound Traffic in HomePlug AV Networks. IEEE Globecom 2006. 2006; p. 1-6.
24. Olempia KJ, Pandeeswaran C, Natarajan P. A Survey on Energy Efficient Contention based and Hybrid MAC Protocols for Wireless Sensor Networks. Indian Journal of Science and Technology [Internet]. 2016 Apr 6; 9(12):1-10.
25. Zhai H, Kwon Y, Fang Y. Performance analysis of IEEE 802.11 MAC protocols in wireless LANs. Wireless Communications and Mobile Computing [Internet]. 2004 Dec 1; 4(8):917-31. Crossref.
26. Pi-ero-Escuer PJ, Malgosa-Sanahuja J, Manzanares-Lopez P. Homeplug-AV CSMA/CA Evaluation in a Real In-Building Scenario. IEEE Communications Letters. 2011; p. 683-5.
27. Berger LT, Schwager A, Escudero-Garzas JJ. Power Line Communications for Smart Grid Applications. Journal of Electrical and Computer Engineering. 2013; p. 1-16. Crossref.
28. Carvallo A, Cooper J. The Advanced Smart Grid: Edge Power Driving Sustainability, 1 ed. Artech House. 2011; p. 266.
29. Latchman H, Srinivas K, Yonge L, Gavette S. Homeplug AV and IEEE 1901: A Handbook for PLC Designers and Users, 1a ed. New Jersey, USA: Wiley-IEEE Press. 2013; p. 384. Crossref.