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Modelling for TDMA under an AFR Scheme over Homeplug AV (HPAV)

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Abstract

Background/Objectives: HPAV uses Time Division Multiple Access (TDMA) for the voice and video package transmission, in order to offer properQoS levels. The main goal of this paper is to propose a model $M^m/M/1/B$ that allows assessing the performance of a Power Line Communication network (PLC) under TDMA, during the transmission of multimedia packages, using a AFR package (Aggregation with Fragment Retransmission). **Methods/Statistic Analysis:** In this paper, the throughput saturation concept for a finite Number N of stations. For that reason, it will be assumed that the package size is fixed of L bits to a rate of C Mbps. In order to analyze the performance of the network supported in TDMA, a model $M^m/M/1/B$ is proposed; such model is based on a Round Robin Scheduler (RR) scheme, according to the MAC structure hybrid for HPAV. **Subject Relevance:** AFR is a scheme that was proposed to reach a high efficiency rate in the layer of Media Access Control (MAC) and that, to date, has only been considered in Wireless networks supported in 802.11n. Additionally, up to date, no models to assess the performance over TDMA applied to HPVA in different bibliographic sources have been found. **Results:** Based on the obtained results, it was possible to observe that the model permits to assess the probability of loss packages, the efficiency MAC over TDMA, the throughput and the levels of delay on a PLC network during a transmission of video and voice under a AFR scheme, according to the number of stations, the size of the containment window and the available bandwidth in the channel. **Application/Improvements:** The model proposed can be considered as a tool in future research papers, for the transmission of Voice and video over HPVA, to assess aspects related to QoS.

Keywords: Home Plug, Powerline, Performance, Throughput, AFR, CSMA/CA

1. Introduction

For HPAV, the media access can be time-based or containment-based, using TDMA (Time Division Multiple Access) and CSMA/CA respectively as mechanisms of media access, where CSMA/CA is meant to be transmitting data packages, whilst TDMA is used for the transmission of packages of Voice and Video, in order to offer appropriate levels of QoS. Additionally, HPAV utilizes a Central Coordinator named CCo, which is in charge of allocating resources and PLC network access[1]. In view of this situation, each station must ask for its space for transmitting within the permitted bandwidth. If the CCo grants its authorization, the station will access the media during a certain period of time within the established space, in the reserved time either for CSMA or TDMA.

On the other hand, HPAV includes a new model to retransmit loss packages, or those that have not been properly received, named AFR. In such packages, the

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information is divided into multiple blocks (PB) of constant length ($PB_{size} = 520\ \text{bytes}$), which are aggregated and transmitted in one frame of great length, retransmitting only those corrupted fragments that could not get to overcome verification of FCS by the receiver[2].

In view of the above, the objective of this paper is to propose a $M^m/M/1/B$ model that allows to assess the performance of a PLC network in state of saturation under an AFR scheme, during the process of multimedia package transmission; it is needed to take into account that within the consulted sources, no evidence of similar research works geared towards Power Line Communications (PLC) or HPAV standard have been found.

2. Concept Headings

2.1 Quality of Service

The function of classifying packages in HPAV is part of the Convergence Layer (CL) and it is responsible for processing Ethernet frames (MSDUs/MAC Service Data Unit) that come from the host and need to be mapped in several transmission queuesor links according to the service quality requirements[3]. This function carries out a classification process based on the following parameters:

- Source address Ethernet, destination address Ethernet, labelled VLAN
- Type de service IPv4, protocol IPv4, source address IPV4, destination address IPv4
- Traffic class IPv6, flow label IPv6, source address IPV6, destination address IPv6
- Source port TCP, destination port TCP
- Source port UDP, destination port UDP

In the Beacon frame, the CCo publishes the schedule to transmit the information by the AVLN stations. In the case of transmission of data packages, the CL identifies, by means of the flow classification process CL, the service required for the transmission priority, either being prioritized or having QoS characteristics (Convergence Layer). All this is established by the CCo and allows the Access according to availability and needs. In HPAV the service based on containment has two periods of Access control. The first corresponds to the (PRP) Priority Resolution Period, followed by the Containment period. PRP is composed by two slots in charge of defining the priority resolution PRS0 and PRS1, through which the MAC HPAV establishes a differentiated access service with 4 Channel Access Priorities CAP (Channel Access Priority) CAPx, x=0,1,2,3. The 4 levels of priority are allocated by the CL, where CAP3 is the highest priority and CAP0 is the lowest[4,5].

When the stations send their priority levels, only those with the highest priority will be granted access to the media during the containment period, causing with this, that the remaining nodes desist and try again in the next period. In case that multiple flows are present in the same station, the system of media access based on containment must select one of the flows for this containment period[4]. Within the Ethernet frames IEEE 802.3, there is a field used to codify VLANsaccording to the norm IEEE 802.1Q. In the context of PLC networks, working on peer-to-peer mode, this field is used to label the frames according to the level of priority established in the PRS slots. This field is composed of 3 bits, reason why it is possible to obtain up to 8 possible values. In Table 1, the values allocated to this field according to the priority level are stated.

Table 1. Mapping between VLAN priority of user and CSMA priority

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

A consequence of the mapping shown in Table 1 is that the frames that carry the user's priority by default have a preferential treatment with regard to priorities of user 1 and 2. In Table 2, the priorities or user that should be allocated to the type of applications are shown.

As fundamental part of the priority resolution mechanism, one can have the PRS (Priority Resolution Slot) and the signals for priority resolution. After the end of each transmission, Home Plug organizes the resolution of priorities in order to manage the traffic by means of two slots of priority resolution (PRS0 y PRS1) and then a containment period is allocated where it is necessary to give approval to the node with the highest priority.

Table 2. Mapping between the type of application and the priority of user

Priority of User	Type of Application
7	Network control. Requirements to maintain and support the architecture of the network.
6	Voice. Characterized by delays >10 ms and thus, maximum jitter.
5	Video or Audio. Characterized delays >100 ms.
4	Controlled load. Business applications that require make reservations in bandwidth.
3	Excellent effort. Type of service "best effort" that an organization should deliver to its most important costumers.
0	Best effort. LAN traffic as it´s known today (This priority of user is currently granted to priorities higher than 1 and 2).
1,2	Bulk transfers and other activities that are permitted in the network but should not have an impact in the use of the network by other users and applications.

2.2 TDMA as a Mechanism of Access to Media HPAV

As the algorithm CSMA/CA does not guarantee a minimum transmission time, the standard HPAV uses the allocation of time intervals of transmission based on TDMA in order to access to media and be free of containments. This system of access to media uses a deterministic allocation of the transmission times of each station[6]. HPAV works with fixed periods. A part of the period is reserved for CSMA where the media can be used by any station (HP1.0, HPGP, HPAV) that requires access to media. The remaining time period is reserved for access by TDMA.

The instant of time in which each of the stations can use one specific time window is defined by CCo. Each station must request its space to transmit within the allowed total bandwidth. If the CCs approve grants approval, the station will be able to access the media during certain periodof time within the established space, whether in the time reserved for CSMA or TDMA.

3. Results

3.1 Throughput in Saturation

In HPAV the number of TDMA slots depends on the number N of stations that are part of the PLC network, which will be established by theCCodynamically, and according to the needs of transmission[7]. Like CSMA, each MAC Frame Stream is divided in blocks of 12 octets, which are encrypted, capsuled in blocks PHY (PB) and packaged in a MPDU (MAC Protocol Data Unit) for its later transmission. In order to modelling the access to media by TDMA, a technique named Round Robin Scheduler (RR)[8] will be used, since it is represented in the Figure 1.

In Figure 1, N sessions are established. Such sessions represent the traffic generated by each one of the N stations part of the PLC network. T_p, $A_i yB$ correspond to the time by slot TDMA, the average size by package in bots for the sessioni and the buffer maximum size by session or maximum number of packages that can be present in the transmission queue. Be f_i the ratio of service for

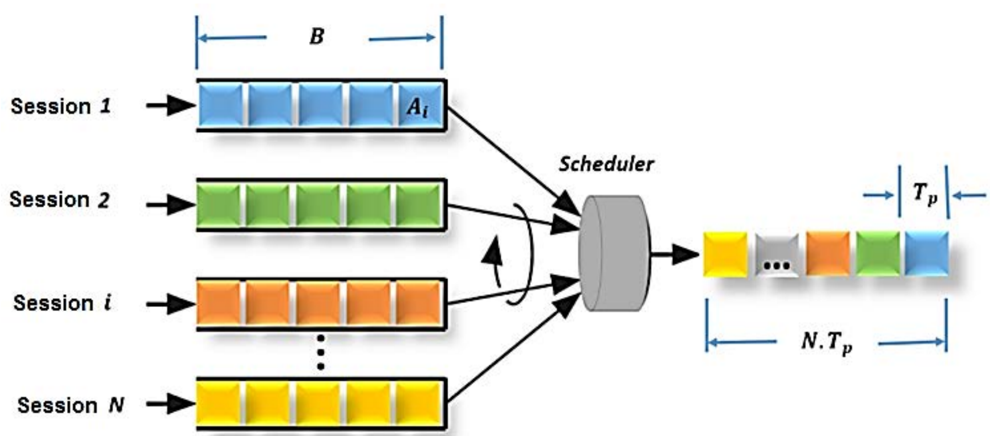

Figure 1. Modelling of TDMA by means of Round Robin Scheduler.

the sessioni, which can be estimated by means of the use of (1):

$$f_i = \frac{A_i}{\sum_{j=1}^{N} A_j} \qquad (1)$$

The value corresponding to the bandwidth for the sessioni (C_i) is,

$$C_i = C.f_i \qquad (2)$$

Assuming a size of constant package for each of the sessions (A_i = Constant), it is possible to say that:

$$f_i = \frac{1}{N}\ , \qquad C_i = \frac{C}{N} \qquad (3)$$

The required time in seconds to take a full turn in the scheme RR (T) is given by:

$$T = \sum_{i=1}^{N} \frac{A_i}{C}[s] \qquad (4)$$

Considering the case in which all the sessions present a constant value of A_i

$$T = \frac{NA_i}{C}[s] \qquad (5)$$

For the particular case of HPAV, the value of $T = T_f = 16.66\ ms$.

In Figure 2, the structure TDMA for HPAV is presented, in which the reserved region is formed by N slots denominated TDMS and each slot TDMS (T_p) represents the time allocated to a particular station in order to transmit. Based on the schemes represented in Figures 1 and 2, the expression is posed[9]:

$$T_s = T_{Header} + \frac{E[L_{pld}]}{C} + RIFS_{AV} + T_{res} + CIFS \qquad (6)$$

Where C is el bit-rate, T_s is the time required to transmit a frame under HPAV, $E[L_{pld}]$ is the average size of the package, $T_{Header}\ y T_{res}$ are the times required to transmit the header of payload, the answer time and the acknowledgement of receipt. Based on the TDMA for HPAV, the number of frames (N_f) that can be transmitted for each TDMS is:

$$N_f = \frac{A_i}{E[L_{pld}]} \qquad (7)$$

The maximum number of packages N_i of length $E[L_{pld}]$ that could get to the queue by sesioni, can be estimated by means of the use of (8):

$$N_i = \left\lfloor \frac{\sigma_i . T}{E[L_{pld}]} \right\rfloor (8)$$

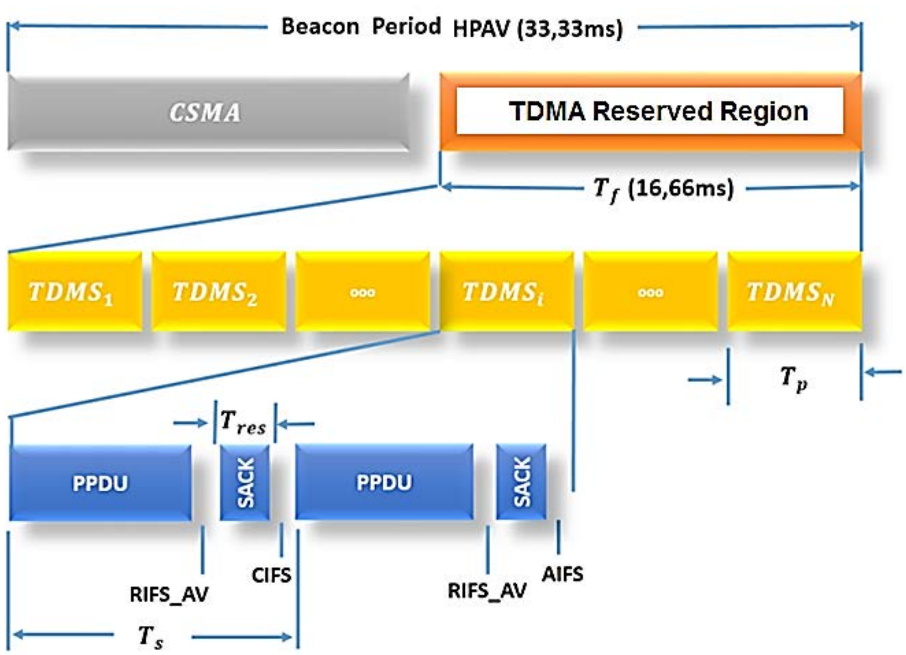

Figure 2. Structure TDMA for HPAV.

Where $\lambda_i y \sigma_i$ corresponds to the rate of receipt of average and maximum packages, respectively, for a stationi. Based on these parameters, in order to estimate such efficiency parameters of the proposed model, a model $M^m/M/1/B$ is proposed, which allows to describe the fact that at least m packages could be part of the queue, and at least a package could be out the such queue (which is coherent with TDMA). In order to estimate the probability that k packages can arrive on a given instant, (such probability complies with a binomial distribution); the following expression is used (9):

$$P_k = \binom{N_i}{k} p^k . q^{N_i - k} \qquad (9)$$

Where p is the probability that a package reaches the queue and $q = 1 - p$. The value of p can be estimated as follows:

$$p = \frac{\lambda_i . T}{N_i . E[L_{pld}]} \qquad (10)$$

In order to estimate the value of Throughput and the delay for each sessioni, it is necessary to estimate the transition matrix $\boldsymbol{P^n}$ in a steady state. For that, matrix **P** is defined, which is coherent to the model $\frac{\frac{M^m}{M}}{\frac{1}{B}}$ and **complies** with an arrangement of $(B+1)\ x\ (B+1)$, where B is the maximum size of the queue or buffer.

$$\mathbf{P} = \begin{vmatrix} q & P_o & 0 & 0 & \cdots & 0 \\ P_2 & P_1 & P_o & 0 & \cdots & 0 \\ P_3 & P_2 & P_1 & P_o & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ P_{B_i} & P_{B_i - 1} & P_{B_i - 2} & P_{B_i - 3} & \cdots & P_o \\ Z_1 & Z_2 & Z_3 & Z_4 & \cdots & Z_{B+1} \end{vmatrix}$$

$$q = P_o + P_1$$

$$Z_j = 1 - \sum_{k=0}^{B_i - j + 1} P_k \ (11)$$

After estimating the matrix of steady state $\boldsymbol{P^n}$, the next process is to estimate the vector of equilibrium vector for the state n, which is formed by $B+1$ elements and can be estimated as follows:

$$S_n = P^n S(0) \qquad (12)$$

The initial condition of the vector of equilibrium distribution to a vector with all its elements in "0", except to the first element of the vector of "1", is observed in the following expression:

$$S(0) = [1\ 0\ 0\ 0 \ldots 0]$$

Once the former process is finished, the next step is to estimate the value ofthroughput corresponding to the sessioni, which can be estimated as follows:

$$Thr_i = \frac{(1 - S_o)A_i}{T}[bps] \qquad (13)$$

Where S_o corresponds to the first element of the vector S_n ($S_o = S_n(0)$).

Where C is el bit-rate, $E[L_{pld}]$ is the average size of the package, $T_{Header} y T_{res}$ are the times required to transmit the package of payload header and to receive the Acknowledgement (ACK) respectively[10].

$$T_{Header} = \frac{MAC_{HDR}}{C} + \frac{PHY_{HDR}}{C_{Control}} \qquad (14)$$

$$T_{Ack} = \frac{L_{Ack}}{C_{Control}} \approx T_{res} \qquad (15)$$

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

In Figure 6, it is possible to observe that each MAC frame stream for HPAV is divided in blocks of 512 bytes, which are encrypted and capsuled in blocks PHY_PB of 520 bytes, according to the structure shown in Figure 3. These PHY_PB are later packaged on a MPDU (MAC Protocol Data Unit) and sent to the physical layer for their transmission[11]. The receiver subsequently reconstructs the MSDU (MAC Service Data Unit), selectively acknowledging the PHY_PB. When all the PHY_PB that form a MSDU have been properly received, the segments are decrypted following the transit to superior layers[12].

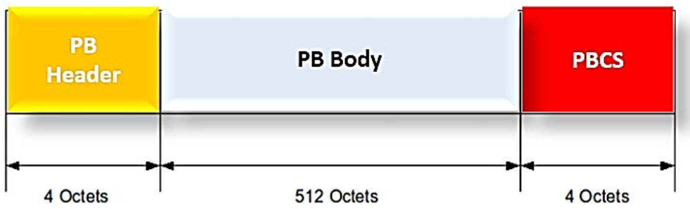

Figure 3. Structure of the block (PHY_PB).

In order to estimate the value of $E[L_{pld}]$ it is necessary to take into account that the maximum time for payload transmissions of a frame over HPAV (Max_FL) cannot be higher than 2501.12μs included RIFS. Hence, the maximum number of bits transmitted by a station will depend on the PHY-rate. Additionally, the number of bits must be multiple of the size of the block PHY_PB adopted by HPAV as a mechanism of capsuling information (PBsize)[13]. In Table 3, the value of the most important parameters of the technical specifications of HPAV standard is summarized.

In (16) the expression is proposed in order to estimate the valyue of $E[L_{pld}]$:

$$E[L_{pld}] = \frac{1}{N}\sum_{i=1}^{N} L_i = \frac{1}{N}\sum_{i=1}^{N}\left\lfloor \frac{C_i(Max\_FL - RIFS)}{PBsize} \right\rfloor . PBsize \quad (16)$$

Where L_i is the number of bits that a station itransmits each time it has access to the channel, l, N is the number of stations in containment, C_i is the PHY-rate of the station iand PBsizecorresponds to the size of the block.

As mentioned before, HPAV includes a new model to retransmit lost packages or that have not been properly received, named AFR. The value of Throghputin state of saturation for a scheme AFR is given by[14]:

$$S_{AFR} = \frac{(1 - S_o)A_{i\_AFR}}{T} \qquad (17)$$

In (17) $E[L]$ does not represent the size of the useful load, but the number of bits expected to be transmittedsuccessfully. It is important to keep in mind that the scheme AFR allows the transmission of fragments successfully to be received, even if some fragments of the frame are damaged. To estimate the value of $E[L]$ the following process is done:

Beithe number of erroneous fragments and m the number of fragments in the frame. Assuming independence and uniform distribution of errors, it can be obtained that[15]:

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

$$P_e^{frag} = 1 - (1 - P_b)^{PB_{pld} + PB_{FCS}} \qquad (18)$$

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

Table 3. Parameters for the specification Homeplug AV[9]

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		

$$E[L] = E[L_{pld}](1 - P_e^{frag}) \qquad (19)$$

Considering that the payload follows a scheme AFR, the expression of A_i will be replaced by:

$$A_{i\_AFR} = N_f . E[L_{pld}](1 - P_e^{frag}) \qquad (20)$$

With

$$P_e^{frag} = 1 - (1 - P_b)^{PB_{pld} + PB_{FCS}} \qquad (21)$$

Where P_e^{frag}, P_b, PB_{pld}, $E[L_{pld}]$ and PB_{FCS} correspond to the probability of error in the fragment or block, the BER, the length of fragment or block (512 bytes), the average length of payload and the length of FCS of the block (4 bytes in the case of HPAV) respectively. Based on the former expressions, the equation that allows estimating the throughput under a scheme AFR over TDMA is (22):

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

$$S_{AFR} = \frac{(1 - S_o)A_{i_{AFR}}}{T}$$

$$S_{AFR} = \frac{(1 - S_o).N_f.E[L_{pld}](1 - P_e^{frag})}{T}[bps] \qquad (22)$$

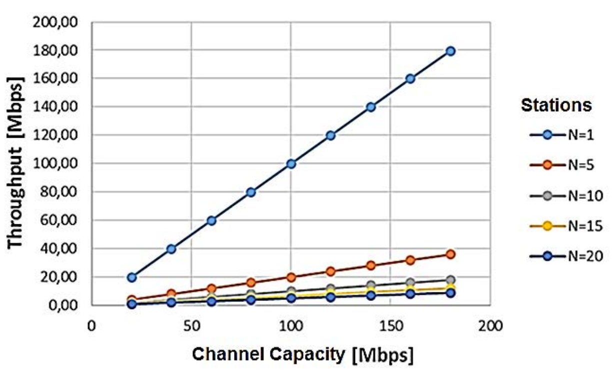

Figure 4. Throughput vs Channel Capacity and number of stations.

In Figure 4, the effect that has the channel capacity and the number of stations over the throughput is shown. There, one can observe that for a network with more than 5 stations, its value will decrease to a 22% of the maximum throughput. Additionally, it is possible to notice a lineal and directly proportional behavior between the channel capacity and the throughput.

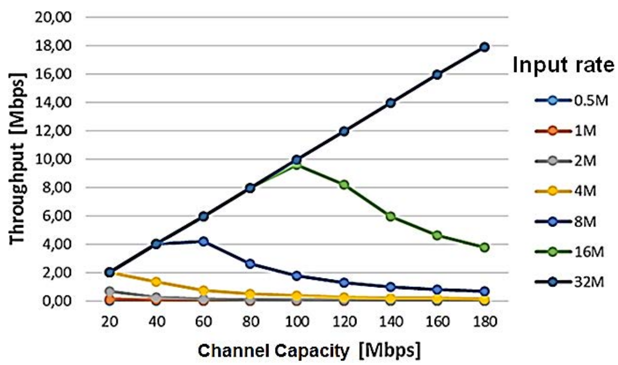

Figure 5. Throughput vs Channel capacity and Input rate.

In Figure 5, it is possible to observe the behavior that the throughput can present in function to the channel capacity and the input rate of a node. The outcome delivers a quite interesting phenomenon, where a growth inasmuch as the input rate and channel capacity can be seen; nonetheless, after a certain point, the value of throughput starts to decrease, despite the fact that both the input rate but the channel capacity is on the increase. This fact suggests thatthese points can be considered as high performance moments, where the system changes to a state of saturation.

3.2 Average Delay of Packages

To estimate the average length of the queue in each sessioni, the following can be used (23):

$$Q_i = \sum_{j=0}^{B_i} i.S_j \qquad (23)$$

Using theorem of little, the average time in which each package must remain in the queue of the session*i*can be estimated as follows:

$$W_i = \frac{Q_i}{S_{AFR}}[s] \qquad (24)$$

Hence, the total delay will be:

$$D_{TDMA} = T_{cola} + T_{giro\_RR} + T_{CSMA} = W_i + T + T_f \qquad (25)$$

$$D_{TDMA} = W_i + 2T_f \qquad (26)$$

In Figure 6, that is the figure that represents the time in queue vs channel capacity and number of stations, it can be observed that the waiting time decreases considerably inasmuch as the PLC channel capacity increases. However, its value grows proportionally to the number of stations, especially when the capacity of the PLC cannel is lower than 80Mbps. In residential surroundings under typical PLC channel conditions, channel capacity can range between 90 Mbps and 120 Mbps, which states that despite an increase of the number of station on a PLC network takes place, the waiting time in queue will not be raised. This last fact favors the QoS levels that can be present in the network.

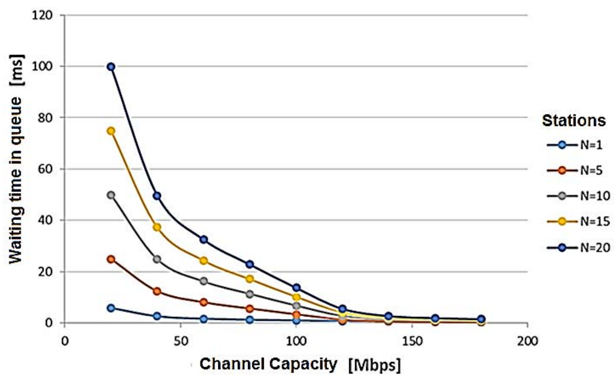

Figure 6. Waiting time in queue vs. Channel capacity and number of stations.

In Figure 7, it can be observed that the capacity of the channel has a great influence on the waiting time in queue on a package, especially when the arrival rates of the packages are on increase. Nonetheless, such situation tends to stabilize, with waiting times quite reduced inasmuch as the channel capacity exceeds120 Mbps.

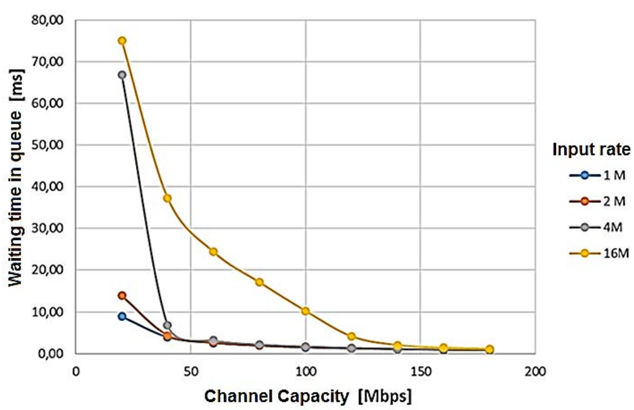

Figure 7. Waiting time in queue vs Channel capacity and input rate.

3.3 Probability of Discarded Packages

A package can be considered as lost when, at arrival, the number of packages in queue in the sessioni is higher than B. In view of the above, and based on the model $M^m/M/1/B$, the probability of loss packages can be estimated by means of the use of (27):

$$P_{Drop} = 1 - \sum_{i=0}^{B} P_i \qquad (27)$$

The efficiency of MAC throughput as:

$$\eta_{MAC} = \frac{T_p}{T_p + T_{oh}^p} \qquad (28)$$

Where:

$$T_{oh}^p = T_{Header} + T_{res} \qquad (29)$$

$$T_p = E\frac{[L_{pld}]}{C} \qquad (30)$$

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

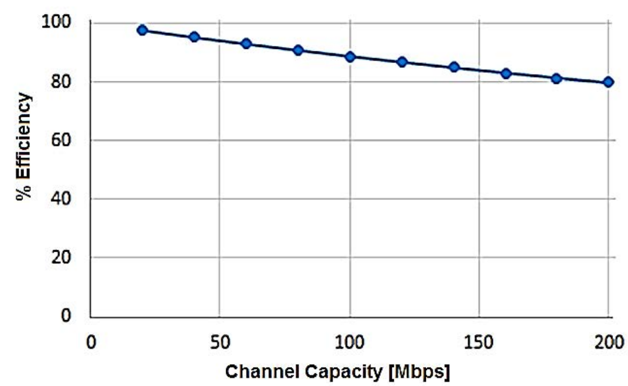

Figure 8. Efficiency MAC for TDMA over HPAV.

In Figure 8, it can be observed that the average of efficiency MAC for TDMA presents maximum and minimum levels of 97, 52% and 79, 72% respectively, and under a behavior inversely proportional to the channel capacity. On the other hand, the efficiency MACfor TDMA is superior to the one obtained in CSMA/CA.

4. Conclusions

An aspect that can be considered as a great contribution to the study of PLC technology follows the proposed model $M^m/M/1/B$, supported on a scheme "Round

Robin Scheduler (RR)", as a strategy in order to represent and estimate the performance of a PLC network, under a multiuser-multiclass context, for TDMAas mechanism to media access in residential surroundings. The model allows to estimate diverse parameters of performance and to assess the behavior of each service that each node demands, which favors the development of future works related to the use of the PLC technology in residential surroundings, taking into account that, up to date, there has not been a model able to represent this kind of scenario, supported in the HPAV standard.

A very important element in the proposed model, has been the inclusion of the scheme named AFR (Aggregation with Fragment Retransmission), in which the information is divided into multiple blocks (PB) of constant length (PB_{size}), for its later transmission in just one frame of great length, retransmitting only the corrupted fragments that have not been approved by the receiver. Scheme that, to date, had not been considered in no model proposed by HPAV by other authors, allowing representing more accurately the behavior of PLC technology. According to the obtained results, it could be observed that the model allows to properlyanalyze the performance of a network during the transmission period allocated for TDMA, where number of stations, the bandwidth available in the channel and the size of the package are shown. All those parameters can greatly affect the values related to the probability of loss packages, the efficiency MAC under TDMA, the throughput and the levels of delay on a PLC network.

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