

## Evaluation of models Hybrid (MH) and Smart (MS) based on game theory for resources allocation in HomeplugAV networks

JUAN C. VESGA

Escuela de Ciencias Básicas Tecnología e  
Ingeniería  
Universidad Nacional Abierta y a Distancia  
Carrera 27 # 40-43 Bucaramanga  
COLOMBIA  
juan.vesga@unad.edu.co

JAVIER E. SIERRA

Vicerrector de Calidad  
Corporación Universitaria del Caribe CECAR  
Ctra. Troncal de Occidente - Km 1 - Via  
Corozal, Sincelejo  
COLOMBIA  
javier.sierra@cecar.edu.co

GERARDO GRANADOS

Escuela de Ciencias Básicas Tecnología e Ingeniería  
Universidad Nacional Abierta y a Distancia  
Carrera 27 # 40-43 Bucaramanga  
COLOMBIA  
gerardo.granados@unad.edu.co

*Abstract:* - The communications standard by powerline HomePlug AV does not have an appropriate resource optimization mechanism for a multiuser environment, which significantly affects the network performance when the number of users increases. In light of the foregoing, it is proposed the use of the Smart Model (SM) that uses the cooperative game theory, and especially the bankruptcy problem and the Shapley value, as a strategy to optimize the allocation of bandwidth on each node, according with the demand in the service, the number of stations and PLC channel conditions.

The article presents a scenario under saturated traffic conditions to validate whether the proposed model (SM-HPAV) operates better than the model that uses HomePlug AV (HM-HPAV). The evaluation process presented favorable results for SM-HPAV which shows that the use of the cooperative game theory, supported on the Shapley value can be regarded as an excellent alternative when performing optimization processes bandwidth in a channel PLC and with the possibility to be implemented in low-cost embedded systems because it does not require complex operations for estimation, significantly improving levels of throughput, delay and efficiency of PLC technology.

*Key-Words:* - Cooperative Game Theory, Homeplug AV, Network Modelling, Powerline Communications, Resources Optimization

### 1 Introduction

The HomePlug AV (HPAV) standard communications is one of the most widely accepted standards on PLC technology, which uses the electrical network as a physical transmission medium, it uses OFDM (*Orthogonal Frequency Division Multiplexing*) as a technique of multiplexing information on the PLC channel. It operates in the range of 1.8 MHz to 28MHz and divides the spectrum into 1055 subcarriers, of which only 917 are active for the American system. HPAV uses adaptive modulation for each subcarrier depending on the channel conditions and uses a Central Coordinator (CCo), which is in charge of making resource allocation and manage access to PLC network [1]. In addition, HPAV has a hybrid medium access mechanism supported by CSMA/CA

and TDMA, where CSMA/CA is designed for transmitting data packets, while TDMA is used for transmission of voice and video packets, in order to provide adequate levels of QoS [2].

Initially, there is a description of the hybrid model which was developed to represent the current state of HPAV standard, called "HomePlug AV Hybrid Model (HM-HPAV)." This in order to evaluate the performance of the HPAV standard for a multiuser scenario, according to diverse needs and types of traffic, linking the medium access mechanism for CSMA/CA (*Carrier Sense Multiple Access with Collision Avoidance*) and TDMA (*Time Division Multiple Access*) simultaneously, something that had not been developed so far and that led to the design of the model.

Later, it is described the development of the proposed model called "SmartModel - HomePlug

AV (SM-HPAV)" which articulates the mechanisms for resource allocation, supported by using the cooperative game theory, focused on the Shapley value as a strategy for resource allocation in each node that is part of the PLC network. The proposed model emerges as a strategy for allocating resources in a PLC network, in order to improve the network performance against the current state of the HPAV standard. At the end of the article, both models will be evaluated, with the purpose of establishing whether there are significant differences in improvement, in a specific scenario and under different traffic needs.

## 2 CONCEPT HEADINGS

### 2.1 Hybrid Model - HPAV (HM-HPAV)

The HPAV standard uses CSMA/CA and TDMA as medium access mechanisms, equitably distributed by transmission period equivalent to two cycles of network. The first region is intended for the transmission of data packets using CSMA / CA. The second region uses TDMA for transmission of voice and video packets [1]. Considering the above, HM-HPAV consists of two stages of modeling: one for CSMA/CA and the other for TDMA. Figure 1 represents the structure for a transmission process by period for HPAV.

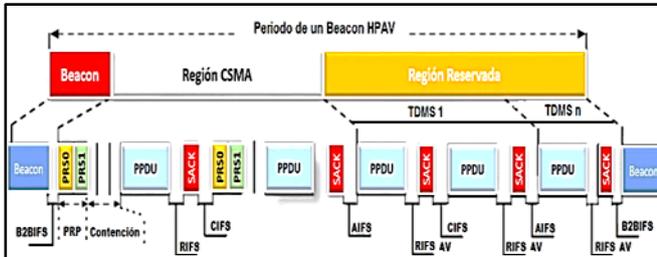


Fig. 1. Structure for a transmission process by period for HPAV (HomePlug AV)

It is important to mention that for practical purposes four possible classes of traffic have been established which flow through the network PLC:Voice, Video, Control and Data. The first two classes will be supported by TDMA and the last two classes by CSMA/CA.

#### 2.1.1 Stage 1 HM-HPAV: Model developed for CSMA / CA

At this early stage, it was considered a model based on the "Weighted Round Robin Scheduler (WRR)" scheme, in order to represent the media access mechanisms by CSMA/CA, considering that the time of access to the medium is not the same for all

nodes that are part of the network. The proposed CSM/CA-HPAV scheme is illustrated in Figure 2.

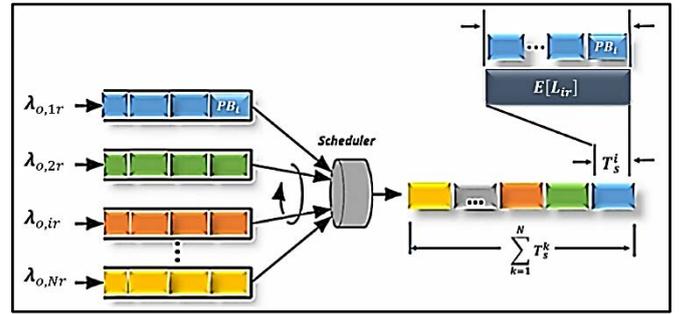


Fig. 2. WRR Schema proposed for CSMA/CA-HPAV

In order to perform an analysis about the queuing model proposed for a WRR scheme, the following considerations are assumed:

- $C$ : Total capacity of the channel [Mbps].
- $C_i$ : Channel Capacity estimated for node  $i$  [Mbps].
- $C_{ir}$ : Channel Capacity estimated for the node  $i$  class  $r$  [Mbps].
- $N_D$ : Number of active sessions that want to transmit in the CSMA/CA region.
- $B_i$ : Maximum size of the queue or buffer for node  $i$
- $w_{ir}$ : Assigned weight to the node  $i$  class  $r$ .
- $\lambda_{o,i}$ : Rate of packet arrival at node  $i$ .
- $\sigma_{ir}$ : Maximum rate of packet arrival at node  $i$ , class  $r$ .
- $E[L_{ir}]$ : Average size of the packet for the session  $i$  class  $r$
- $T_{HPAV}$ : Period HPAV ( $2/f_{red} = 33.33$  ms)
- $T_{CSMA}$ : Period for CSMA / CA in HPAV ( $T_{HPAV}/2$ )
- $T_{TDMA}$ : Period for TDMA in HPAV ( $T_{HPAV}/2$ )
- $k_M$ : Activity Factor of voice or video traffic on the PLC network.

The arrival rate of size packets  $PB_{size} = 520$  bytes for node  $i$  and class  $r$  ( $\lambda_{B,ir}$ ), is calculated as follows (1):

$$\lambda_{B_{ir}} = \left[ \frac{\lambda_{o,ir}}{PB_{size}} \right] \quad (1)$$

The maximum rate of blocks arrival ( $\sigma_{B_{ir}}$ ) and the maximum number of blocks that can reach the node  $i$  and class  $r$  per period HPAV ( $N_{B_{ir}}$ ) is (2)(3):

$$\sigma_{B_{ir}} = \left[ \frac{\sigma_{ir}}{PB_{size}} \right] \quad (2)$$

$$N_{B_{ir}} = \sigma_{B_{ir}} \cdot T_{HPAV} \quad (3)$$

The probability of arrival of a block to the node  $i$  and class  $r$  ( $P_{B_{ir}}$ ) it is given by (4):

$$P_{B_{ir}} = \frac{\lambda_{B_{ir}}}{\sigma_{B_{ir}}} \quad (4)$$

In view of the above, the probability of  $k$  blocks arrival during a time step to the node  $i$  and class  $r$  is (5):

$$P_k^{ir} = \binom{N_{B_{ir}}}{k} P_{B_{ir}}^k (1 - P_{B_{ir}})^{N_{B_{ir}} - k} \quad (5)$$

*Throughput Estimation.*

To estimate the value of throughput and the delay for the  $i$  node, it is necessary to calculate the transition array  $\mathbf{P}^n$  in a stable condition. For this the  $\mathbf{P}$  array is defined, associated with the model  $M^{N_D}/M/1/B_i$  which follows an array of  $(B_i + 1) \times (B_i + 1)$ , where  $B_i$  is the maximum size of the queue or buffer for the  $i$  node and  $N_D$  is the number of active sessions with a need of transmit class  $r$ .  $\mathbf{P}_{ir}$  structure array is:

$$\mathbf{P}_{ir} = \begin{pmatrix} q^{ir} & P_0^{ir} & 0 & 0 & \dots & 0 \\ P_2^{ir} & P_1^{ir} & P_0^i & 0 & \dots & 0 \\ P_3^{ir} & P_2^{ir} & P_1^i & P_0^i & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ P_{B_i}^{ir} & P_{B_i-1}^{ir} & P_{B_i-2}^{ir} & P_{B_i-3}^{ir} & \dots & P_0^{ir} \\ Z_1 & Z_2 & Z_3 & Z_4 & \dots & Z_{B_i+1} \end{pmatrix} \quad (6)$$

$$q^{ir} = P_0^{ir} + P_1^{ir} \quad (6)$$

$$Z_j = 1 - \sum_{k=0}^{B_i-j+1} P_k^{ir} \quad (7)$$

After calculating the array of steady state  $\mathbf{P}_{ir}^n$ , it is proceeded to calculate the equilibrium distribution vector for the  $n$  state, which is made up by  $B_i + 1$  elements and can be estimated as follows (8):

$$S_n = P^n S(0) \quad (8)$$

The initial condition of the equilibrium distribution vector corresponds to a vector with all its elements in "0", except the first element of the vector, which will record a value of "1", as it is shown in the expression (9):

$$S(0) = [1 \ 0 \ 0 \ 0 \ \dots \ 0] \quad (9)$$

In view of what it was said before, the value of the throughput for the node  $i$  class  $r$ , can be estimated as follows (10):

$$Thr_{ir} = \frac{(1 - S_{oir})E[L_{ir}]}{E[T_s^{ir}]} [bps] \quad (10)$$

Where  $S_{oir}$  corresponds to the first element of the vector  $S_n$  ( $S_{oir} = S_n(0)$ ) and  $E[T_s^{ir}]$  is the average time required for the node  $i$  class  $r$  to transmit a frame under the CSMA/CA scheme.

For the particular case of CSMA/CA, because it is a medium access mechanism based on contention, it is necessary to calculate the average length of a timeslot considering three possible states in which the channel can be found during the transmission process (free, transmitting or colliding)[3]. Based on the proposed model by [4][5], the value  $E[T_s^i]$  can be estimated using the following process:

Let  $P_{tr}$  the probability that at least one station transmits, taking into account that each station transmits with a probability  $\tau$ . The expression for  $P_{tr}$  is (11):

$$P_{tr} = 1 - (1 - \tau)^N \quad (11)$$

In [6] the value of  $\tau$  can be calculated as follows (12):

$$\tau = \frac{1}{N} \sqrt{E[T_c]} \quad (12)$$

Where  $E[T_c]$  is the average collision time normalized by *timeslot*.

A collision occurs when two or more stations initiate simultaneously a process of transmission. Therefore, defines  $P_s$  as the probability that a station trasmits successfully and that the  $N-1$  remaining stations maintain a listening state (of the network). The  $P_s$  value is given by (13):

$$P_s = \frac{N \cdot \tau \cdot (1 - \tau)^{N-1}}{P_{tr}} = \frac{N \cdot \tau \cdot (1 - \tau)^{N-1}}{1 - (1 - \tau)^N} \quad (13)$$

Finally, the expression that allows to calculate the value of  $E[T_s^i]$  is (14):

$$E[T_s^i] = (1 - P_{tr})\sigma + P_{tr} \cdot P_s \cdot T_{s,i} + P_{tr} \cdot (1 - P_s) \cdot T_{c,i} \quad (14)$$

where:

$\sigma$ : Duration of an empty *timeslot* under free channel conditions ( $\sigma = 35.84\mu s$  for HPAV)

$T_{s,ir}$ : Time that it takes for a successful transmission for the node  $i$  class  $r$

$T_{c,ir}$ : Time that it takes to be detected a collision for the node  $i$  class  $r$

$1 - P_{tr}$ : Probability of a *timeslot* passes normally or in a state of free channel.

$P_{tr} \cdot P_s$ : Probability of containing a successful transmission.

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

Given that HPAV does not have a mechanism for the allocation of resources, it is necessary to estimate the probability that a station uses the channel PLC according to service demand. Therefore, the probability of channel usability is (15):

$$P_{a_{ir}} = \frac{P_{tr} \cdot P_s \cdot \lambda_{B_{ir}}}{\sum_{j=1}^{N_D} \sum_{s=1}^R \lambda_{B_{js}}} \quad (15)$$

The value of  $P_{a_{ir}}$  can be considered as the weight assigned to the channel usage of node  $i$  class  $r$  (16).

$$w_{ir} = P_{a_{ir}} \quad (16)$$

When HPAV uses a hybrid medium access mechanism needs to define  $k_M$  factor, which take the value of "1" in the presence of voice or video traffic, otherwise it will adopt a value of "0". Then, the  $C_i$  value can be calculated in (17):

$$C_{ir} = \left[ \frac{C}{(1+k_M) \cdot P_{a_{ir}}} \right] \cdot T_{OFDM} \quad (17)$$

Where the minimum time of the channel allocation equivalent to the time of an OFDM symbol for HPAV ( $T_{OFDM} = 40,96\mu s$ ) [1].

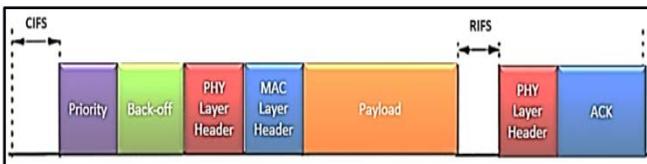


Fig. 3. Structure of a HPAV frame in the CSMA region.

Taking into account the structure of the frame as shown in Figure 3, the values of  $T_{c,ir}$  and  $T_{s,ir}$  can be defined as follows for HPAV standard (18):

$$T_{s,ir} = T_{Priority} + T_{Backoff} + T_{Header} + \frac{E[L_{ir}]}{C_{ir}} + RIFS + T_{res} + CIFS \quad (18)$$

$$T_{c,ir} = T_{Priority} + T_{Backoff} + T_{Header} +$$

$$\frac{E[L_{ir}]}{C_{ir}} + CIFS \quad (19)$$

$$T_{Priority} = PRS0 + PRS1 \quad (20)$$

$$T_{Header} = \frac{MAC_{HDR}}{C} + \frac{PHY_{HDR}}{C_{Control}} \quad (21)$$

$$T_{Ack} = \frac{L_{Ack}}{C_{Control}} \approx T_{res} \quad (22)$$

$MAC_{HDR}$  and  $PHY_{HDR}$  corresponds to the MAC and the physical header (bits) respectively.  $C_{Control}$  is the transmission rate of the control bits and  $L_{Ack}$  is the length of the acknowledgment (ACK). Moreover,  $C_{ir}$  is the bit-rate at the node  $i$  class  $r$ ,  $T_{Header}$  and  $T_{res}$  are the times required to transmit the header payload packet and receive the acknowledgment respectively.

Because the  $T_{Backoff}$  corresponds to the number of *timeslots* that the containment process must wait (Whose value is assigned randomly between  $[0, CW]$ ), it will be considered a contention window value for purposes of calculating  $W = (CW_{max} + 1)/2$ , where  $CW_{max} = 63$  for HPAV [1]. Therefore, the average value of  $T_{Backoff}$  is given by (23):

$$T_{Backoff} = \sigma \cdot (CW_{max} + 1)/2 \quad (23)$$

In order to calculate the average size of the packet  $E[L_{ir}]$ , it should be aware that the maximum time for the payload transmission in a frame on HPAV ( $Max\_FL$ ) cannot exceed  $2501.12\mu s$  including RIFS. Moreover, the number of bits must be a multiple of the block size  $PHY\_PB$  adopted by HPAV as mechanism of encapsulation of the information (PBsize). In Table 1 it is summarized the value of the most important parameters that are part of the technical specifications of the HPAV standard.

Table1. Technical specifications related to the HomePlug AV standard

Parameter	Value	Parameter	Value
Max_FL	2501,12	Head Time	110,48

Response Time	140,48	Frame Head	26 bytes
RIFS Default	100 μs	Slot time (σ)	35,84 μs
RIFS_AV	30 - 160	B2BIFS	90 μs
CIFS	100 μs	BIFS	20 μs
PRS0,PRS1	35,84 μs	EIFS_AV	2920,64
PB Payload	512	PBsize	520 bytes
PB Head	8 bytes		

Considering the above, the following optimization model is proposed:

$$\max E[L_{ir}] \quad (24)$$

subject to:

$$t_{Tx\_Pld} \leq Max_{FL} - RIFS$$

$$C_{ir} \cdot t_{Tx\_Pld} \leq \lambda_{o,ir} \cdot T_{HPAV}$$

$$E[L_{ir}] = \left[ \frac{C_{ir} \cdot t_{Tx\_Pld}}{PBsize} \right] \cdot PBsize$$

#### Throughput under AFR scheme

For the proposed model is considered that HPAV includes a new mechanism for retransmitting lost packets or which have not been received properly, called AFR (*Aggregation with Fragment Retransmission*). An AFR is a scheme in which information is divided into multiple blocks (PB) of constant length ( $PB_{size}$ ), which are added and transmitted in a single frame of large length. The MAC layer transmits the large frame and only retransmits corrupt fragments that could not pass the FCS check by the receptor. In view of the above, for an AFR scheme the value  $E[L_{AFR}]$  does not represent the size of the payload, but the number of bits expected to be transmitted successfully [7].

Based on [8], the value of  $E[L_{AFR}]$  can be calculated by using the following expressions (25)(26):

$$E[L_{ir\_AFR}] = E[L_{ir}](1 - P_e^{frag}) \quad (25)$$

with,

$$P_e^{frag} = 1 - (1 - P_b)^{PBsize} \quad (26)$$

Where  $P_e^{frag}$ ,  $P_b$  and  $PB_{size}$  correspond to the probability of error in the fragment or block, the BER and the block size (520 bytes) respectively.

Finally, the resulting expression that allows to estimate the throughput for the node  $i$  class  $r$ , under a scheme AFR and according to the proposed model is defined by (27)(28):

$$Thr_{ir\_AFR} = \frac{(1 - S_{oir}) P_{tr} \cdot P_s \cdot E[L_{ir}](1 - P_e^{frag})}{(1 - P_{tr})\sigma + P_{tr} \cdot P_s \cdot T_{s,ir} + P_{tr} \cdot (1 - P_s) \cdot T_{c,ir}} [bps] \quad (27)$$

$$Thr_{i\_AFR} = \sum_{r=1}^R Thr_{ir\_AFR} \quad (28)$$

#### Average delay of packets

The average number of queued packets ( $L_{Q_i}$ ) for the proposed model, depending on the traffic intensity and the system capacity is given by (29):

$$L_{Q_{ir}} = PB_{size} \cdot \sum_{j=0}^{B_i} j \cdot S_j \quad (29)$$

By Little theorem, the average time in which each package must remain in the queue at node  $i$  can be estimated as follows (30):

$$W_{Q_{ir}} = \frac{L_{Q_{ir}}}{Thr_{ir\_AFR}} [s] \quad (30)$$

$$W_i = \sum_{r=1}^R W_{ir} \quad (31)$$

Therefore, the total average delay for node  $i$  will be (32):

$$D_{ir} = W_{Q_{ir}} + T_{HPAV} \quad (32)$$

#### 2.1.2 Stage 2 HM-HPAV: Model developed for TDMA

Since the CSMA/CA algorithm does not guarantee a minimum transmission time, the HPAV standard assigns transmission timeslots based on TDMA (*Time Division Multiple Access*) in order to access the medium, free of containments and under a deterministic allocation of transmission times of each station [6].

The point of time at which each of the stations can use a particular timeslot is defined by the CCo. Each station must request the space to transmit within the total allowed bandwidth. If CCo allows, the station can access the medium for a certain period of time within the space provided, either in the time reserved for CSMA or TDMA, maintaining

a synchronization status by detecting the zero crossings of electrical network and playing the clock function.

In HPAV the number of TDMA slots is set by the CCo in a dynamic and equitable manner, according to the number of stations or active sessions that want to transmit [1]. To model the media access mechanism by TDMA it will be used a technique known as "Scheduler Round Robin (RR.)" [9], which is shown in Figure 4.

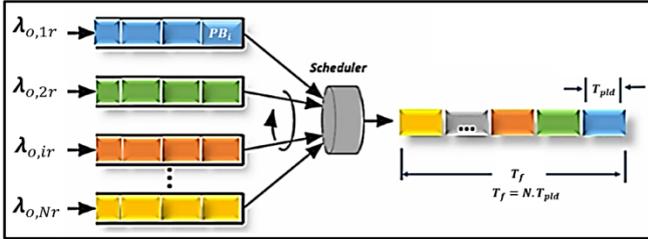


Fig. 4. TDMA Modeling by Round Robin Scheduler

$N$  sessions are established in Figure 24, which represent the traffic generated by each of the stations that are part of the PLC network.  $T_p$ ,  $\lambda_{o,ir}$  and  $B$  correspond to the *timeslot* for TDMA, the rate of packet arrival for the node  $i$  class  $r$  and the maximum buffer size per session (Maximum number of packets that can be queued for transmission). The time required in seconds for a complete turn in the RR(T) scheme, under HPAV is given by  $T = T_{HPAV} / (1 + k_D)$ , where  $k_D$  takes a value of "1" if there is data packets activity and "0" if there is not activity. In most cases, the value of  $T = T_f = 16.66 \text{ ms}$ , when considering a network frequency of 60Hz.

**Throughput estimation**

In Figure 5, the structure of TDMA for HPAV is represented, in which the reserved region consists  $N$  slots called TDMS and each TDMS ( $T_p$ ) slot represents the time allocated to a particular station so that it can transmit (33).

$$T_p = \frac{T}{N} \tag{33}$$

Based on the schemes shown in Figures 4 and 5, the transmission time of a frame  $T_s^i$  for node  $i$  is (34):

$$T_s^{ir} = T_{Header} + \frac{E[L_{ir}]}{C_{ir}} + RIFS_{AV} + T_{res} + CIFS \tag{34}$$

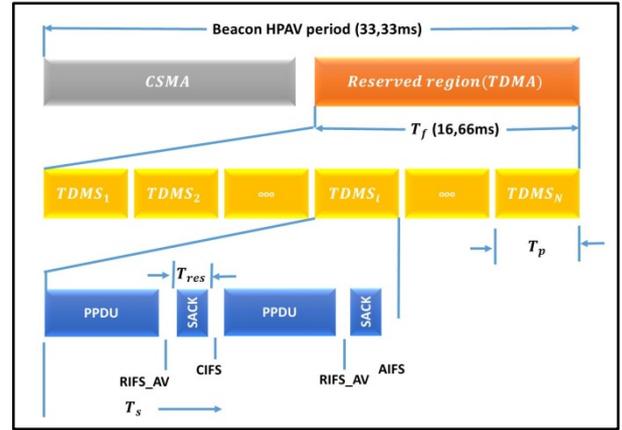


Fig. 5. Structure TDMA for HPAV

Where  $C_{ir}$  is the bit-rate for the node  $i$  class  $r$ ,  $T_s$  is the required time to transmit a frame under HPAV,  $T_{Header}$  and  $T_{res}$  are the required times to transmit the *payload* header and the response time or acknowledgment (ACK) respectively.  $E[L_{ir}]$  is the average packet size, and can be calculated by using (23) and (24).

To estimate the capacity of  $C_i$  channel, it is necessary to note that the minimum allocation time of channel equivalent to the time of an OFDM symbol for HPAV ( $T_{OFDM} = 40,96 \mu s$ ) and the available capacity should be divided between the number of nodes which are part of the PLC network [1]. Also, it is important to remember that HPAV by making use of a hybrid medium access mechanism may cause that the total capacity of the channel will be divided into two, allocating a half for CSMA / CA and the other half for TDMA, according to the value of the  $k_D$  factor. Therefore, the corresponding value to the capacity for the session  $i$  ( $C_{ir}$ ) is given by (35):

$$C_{ir} = \left[ \frac{C}{(1 + k_D) \cdot N \cdot T_{OFDM}} \right] \cdot T_{OFDM} \tag{35}$$

Based on the TDMA structure for HPAV, the number of *frames* ( $N_f$ ) that may be transmitted for each TDMS is (36):

$$N_{f,ir} = \left\lfloor \frac{T_p}{T_s^{ir}} \right\rfloor \tag{36}$$

The parameters that correspond to the arrival rate of block size  $PB_{size} = 520$  bytes ( $\lambda_{B,ir}$ ), the maximum rate of block arrival ( $\sigma_{B,ir}$ ), the maximum number of blocks that can arrive by HPAV period ( $N_{B,ir}$ ), the probability of arrival of a block ( $P_{B,ir}$ ), the probability that  $k$  blocks arrive during a *timestep* ( $P_k^{ir}$ ) can be calculated in the

same way as it was done in stage 1. Equations (1) to (5).

To estimate the value of *Throughput* and the delay per session, it is necessary to recalculate the transition array  $P^n$  at steady state and the distribution vector of equilibrium for  $n$  state by using equations (6) to (9).

Based on the previous expressions, the resulting expression that permits to estimate the throughput for the node  $i$  class  $r$  under an AFR scheme and according to the proposed model is defined by (37) (38):

$$Thr_{ir\_AFR} = \frac{(1 - S_{oir}) \cdot N_{f,ir} \cdot E[L_{ir}] (1 - P_e^{frag})}{T} [bps] \quad (37)$$

$$Thr_{i\_AFR} = \sum_{r=1}^R Thr_{ir\_AFR} \quad (38)$$

*Average delay of packets.*

To calculate the average length of the queue at each node  $i$  class  $r$ , the following expression is used (39):

$$L_{Q_{ir}} = PB_{size} \cdot \sum_{j=0}^{B_i} j \cdot S_j \quad (39)$$

By the use of Little's theorem, the average time in which each package must remain in the queue at node  $i$  can be estimated as follows (40) (41):

$$W_{Q_{ir}} = \frac{L_{Q_{ir}}}{Thr_{ir\_AFR}} [s] \quad (40)$$

$$W_i = \sum_{r=1}^R W_{ir} \quad (41)$$

Therefore, the total average delay for node  $i$  class  $r$  will be:

$$D_{ir} = W_{Q_{ir}} + T_{HPAV} \quad (42)$$

*Probability of discarded packets and efficiency of the transmission process*

A packet can be considered lost when in its arrival, the number of queued packets in the session  $i$  is greater than  $B$ . In view of the above and based on the model  $M^m/M/1/B$ , the probability of lost packets both for CSMA and TDMA can be calculated by expression (43):

$$P_{Drop} = 1 - \sum_{i=0}^B P_i \quad (43)$$

The  $n$  efficiency both for CSMA and TDMA can be calculated by using the following expression:

$$\eta = \frac{\lambda_{o,ir}}{Thr_{AFR}^i} \quad (44)$$

## 2.2 Smart Model–Homeplug AV(SM-HPAV)

For the development of the Smart Model, there was considered a network with  $N$  nodes and  $R$  classes of traffic with packets with arrival and service times that follow an exponential distribution, under a scheme "Weighted Round Robin Scheduler (WRR)" where the nodes that are part of the network have different access times to the channel.

As HPAV lacks a method for allocating resources, the SM-HPAV will use the Shapley Value as a strategy for resource allocation in the PLC channel, which is supported in the cooperative game theory, in order to establish a  $w_{ir}$  weight associated with each node  $i$  class  $r$ , which is related to the number of packets that each node can transmit, depending on the need of the service, per period  $T = T_{HPAV}$  and equivalent to one full turn of the scheduler.

In addition, SM-HPAV divides the channel into sub-channels  $m$  to allow multiple nodes to transmit simultaneously, increase Throughput levels and reduce levels of delay that can occur when performing voice or video transmission processes. For practical purposes it is considered that the number of sub-channels is equal to the number of nodes that are part of the network ( $m = N$ ). The division of the channel into several sub-channels not only allows multiple nodes to transmit simultaneously, but also a node can make use of more than one of the available sub-channels  $m$  in the BW allocated, as illustrated in Figure 6.

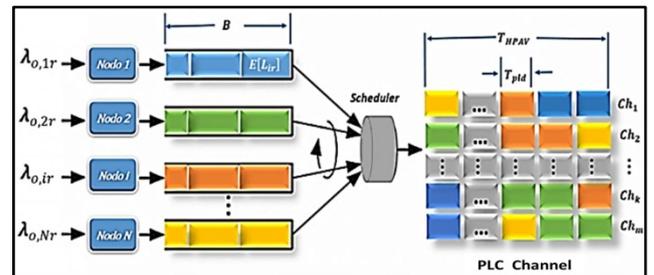


Fig. 6. SM-WRR Scheme proposed for HPAV

In order to perform an analysis about the SM-HPAV, the following considerations will be used:

- $C$ : Total capacity of the channel [Mbps].
- $C_k$ : Sub-channel  $k$  capacity [Mbps].
- $C_i$ : Channel capacity assigned for node  $i$  [Mbps].

$C_{ir}$ : Channel capacity assigned for node  $i$  class  $r$  [Mbps].

$m$ : Number of sub-channels in which the PLC channel is divided.

$B_i$ : Maximum size of the queue or buffer for the node  $i$ .

$BW_{ir}$ : BW value assigned to the node  $i$  class  $r$  by Shapley Value.

$T_{HPAV}$ : time step or time that the Scheduler takes in a spin. In the case of HPAV, this value is equal to  $2f_{red} = 33.33ms$ .

$\lambda_i$ : Packet arrival rate at node  $i$ .

$\lambda_{ir}$ : Packet arrival rate at node  $i$  class  $r$

$E[L_i]$ : Payload average size for the node  $i$  class  $r$

### Throughput Estimation.

Considering that the allocated BW is not the same for all nodes that are part of the network, it is necessary to establish the following relationship (45):

$$C_{ir} = BW_{ir} \quad (45)$$

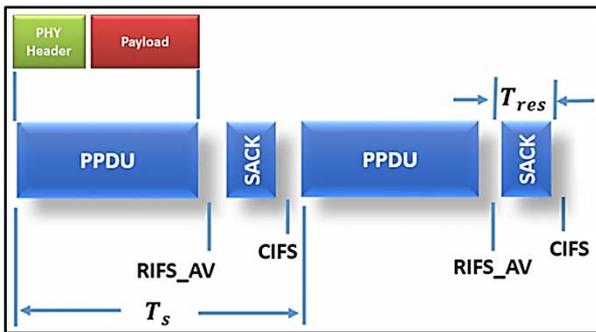


Fig. 7. Structure of a frame by TDMA supported by HPAV

Figure 7 shows the structure of a frame by TDMA supported by HPAV, where it incorporates a PPDU that is composed of a PHY header ( $PHY_{Header}$ ) and a payload ( $E[L_d]$ ). The time required to perform a process of transmission of a frame to the node  $i$  class  $r$  is given by (46):

$$T_{s,ir} = T_{Header} + \frac{E[L_{ir}]}{C_{ir}} + RIFS_{AV} + T_{res} + CIFS \quad (46)$$

$T_{Header}$  y  $T_{res}$  correspond to the time required to transmit the payload header and the response time or acknowledgment (ACK) respectively.  $E[L_{ir}]$  is the average packet size for the node  $i$  class  $r$ , which can be calculated using the equations (23) and (24).

As in the hybrid model, the corresponding parameters to the arrival rate of the block size  $PB_{size} = 520$  bytes ( $\lambda_{B,ir}$ ), the maximum rate of

arrival of blocks ( $\sigma_{B_{ir}}$ ), the maximum number of blocks that can arrive by period HPAV ( $N_{B_{ir}}$ ), the probability of arrival of a block ( $P_{B_{ir}}$ ) and the probability that  $k$  blocks arrive during a time step ( $P_k^{ir}$ ) can be calculated using equations (1) to (5).

To estimate the value of the Throughput and the delay per session, the transition array  $P^n$  at a steady state will be recalculated and the distribution vector of equilibrium for the state  $n$  by using equations (6) to (9).

Based on the previous expressions, the resulting expression that allows the estimation of the Throughput for node  $i$  class  $r$  under an AFR scheme and according to SM-HPAV is defined by (47) (48):

$$Thr_{ir_{AFR}} = \frac{(1 - S_{oir}) \cdot E[L_{ir}](1 - P_e^{frag})}{T_{s,ir}} [bps] \quad (47)$$

with,

$$Thr_{i_{AFR}} = \sum_{r=1}^R Thr_{ir_{AFR}} \quad (48)$$

To calculate the average length of the queue in each node  $i$  class  $r$ , the expression (49) is used:

$$L_{Q_{ir}} = PB_{size} \cdot \sum_{j=0}^{B_i} j \cdot S_j \quad (49)$$

When using the Little theorem, the average time in which each packet must remain in the queue at node  $i$  can be estimated as follows (50):

$$W_{Q_{ir}} = \frac{L_{Q_{ir}}}{Thr_{ir_{AFR}}} [s] \quad (50)$$

with,

$$W_i = \sum_{r=1}^R W_{ir} \quad (51)$$

Therefore, the total average delay for node  $i$  class  $r$  is:

$$D_{ir} = W_{Q_{ir}} + T_{HPAV} \quad (52)$$

### Probability of discarded packets and efficiency of the transmission process

Finally, equations 43 and 44 are used to calculate the probability of lost packets and efficiency of the model.

### Allocation of resources in the frequency and time domain

Some basic parameters that help to understand the way in which the frequency and the time domain

will be assigned for each node  $i$  class  $r$  are presented below.

The expression used to calculate the capacity of the  $k$  sub-channel uses expression (53):

$$C_k = \frac{1}{m} \sum_{i=1}^N \sum_{r=1}^R BW_{ir} \quad (53)$$

The PLC channel can be represented as an array  $Z$  of  $m \times N_{OFDM}$ , where  $m$  is the number of sub-channels and  $N_{OFDM}$  is the number of OFDM symbols by HPAV period. The expression (54) is used to calculate the value of  $N_{OFDM}$ :

$$N_{OFDM} = \left\lfloor \frac{T_{HPAV}}{T_{OFDM}} \right\rfloor = \left\lfloor \frac{33.33 \text{ ms}}{40.96 \text{ } \mu\text{s}} \right\rfloor = 813 \quad (54)$$

Each box in the array  $Z$  corresponds to a portion of the frequency-time domain. Therefore, the total of boxes ( $N_C$ ) of the  $Z$  array is given by (55):

$$N_C = m \cdot N_{OFDM} \quad (55)$$

$P_{C,ir}$  is the probability of boxes allocation of the array  $Z$  to the node  $i$  class  $r$ , where (56):

$$P_{C,ir} = \frac{BW_{ir}}{\sum_{i=1}^N \sum_{r=1}^R BW_{ir}} \quad (56)$$

Thus, the number of assigned boxes to the node  $i$  class  $r$  is given by (57):

$$N_{C,ir} = \lfloor N_C \cdot P_{C,ir} \rfloor \quad (57)$$

The number of sub-channels that will be used by node  $i$  for the transmission of packets class  $r$  can be estimated as it follows (58):

$$N_{CH,ir} = \left\lfloor \frac{BW_{ir}}{C_k} \right\rfloor \quad (58)$$

### 2.3 Estimation of routing probabilities for SM-HPAV model supported on queuing networks

The formation of queues or waiting lines is a common phenomenon in information and communication systems, which occur when the demand of a service is higher than the attention capacity of the system. For this reason, long time ago the queuing theory has been used as a strategy to model traffic that circulates in various

network systems and the PLC networks are not the exception.

Queuing theory was first proposed by *Agner Kraup Erlang* (Denmark, 1878-1929) in 1909 as a strategy to analyze the problems of telephone traffic congestion and from which a solution to the uncertain demand for the service present in the telephone system of Copenhagen will be provided. Since then, Queuing theory is considered as a very important tool that allows you to model, analyze and solve various problems associated to congestion processes in input and output systems [10].

A queuing system can be considered as an appropriate strategy to evaluate the level of efficiency of a system in relation to the arrival, wait and attention times; as well as the number of customers that arrive, remain in the queue, drop out or that are finally served; which allows to identify the optimal levels of capacity and attention, in order to minimize the percentage of customers who can leave the system and maintain an adequate level of performance [11].

A queuing network can be defined as a set of interconnected nodes, which operate asynchronously and concurrently establishing routing policies between nodes that are part of the network red [12]. The use of queuing networks is considered as a very important tool for modeling communication systems because it allows describing the paths or routing policies adopted in the same way as the stochastic processes that describe the flowing traffic through the network [13]. In the case of the PLC multiservice network<sup>1</sup>, an open queue network will be used, because the entry of packets to each node and their output of the system to internet are possible.

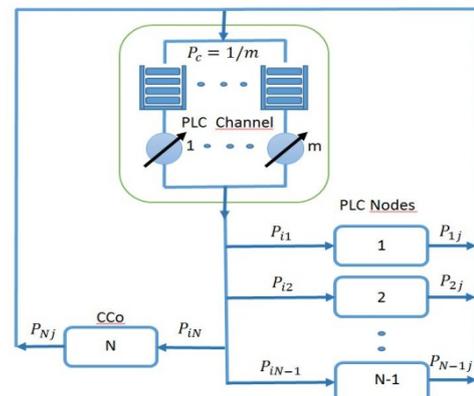


Fig. 8. General model of the multiservice network on PLC

<sup>1</sup> Multiservice network means a multiuser and a multiclass scenario

Figure 8 shows the corresponding scheme of the queues network proposed to model a multiservice network on PLC. In the scheme a node is represented as a subsystem with lines that represent each incoming and outgoing traffic. Each traffic line is accompanied by a probability  $P_{ij,r}$  which represents the probability that a packet is sent from node  $i$  to node  $j$  and that it belongs to class  $r$ , with  $r = \{1: \text{voice}, 2: \text{video}, 3: \text{Control} 4: \text{data}\}$ . The node  $N$  is the node that will play the role of CCo.

In addition, the model shows that the PLC channel is divided into  $m$  sub-channels, which allows that multiple users can share the spectrum of a channel by distributing resources both in frequency and time, in order to optimize network performance, ensuring different QoS levels depending on the bandwidth allocated [14].

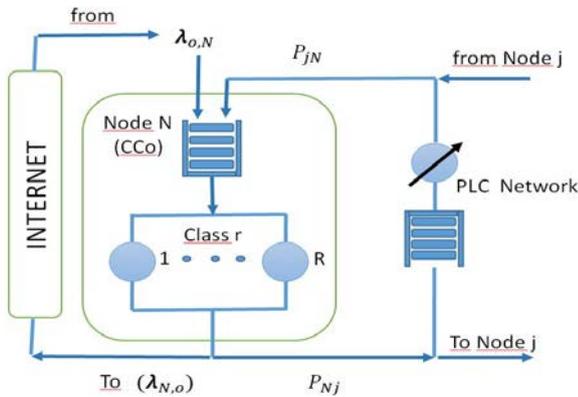


Fig. 9. Model for the node CCo

Figure 9 shows the corresponding model of the subsystem that belongs to the node  $N$  (CCo), which goes from and to each of the nodes, according to the probability of routing established  $P_{iN}$ , which corresponds to the probability that traffic is sent from node  $i$  to node  $N$ . Moreover  $P_{Ni}$  is the probability that traffic is sent from node  $N$  to node  $i$ , and its value depends on the number of existing nodes in the PLC network. The  $\lambda_{o,Nr}$  and  $\lambda_{Nr,o}$  values correspond to incoming and outgoing traffic of node  $N$  class  $r$  respectively.

The subsystem that corresponds to node  $i$  is presented in Figure 10. There the incoming and outgoing traffic from the PLC network is represented, according to the routing probabilities  $P_{ji,r}$  and  $P_{ij,r}$  respectively.

Then, the proposed methodology to calculate the routing probabilities between nodes by class of service for a network supported by PLC is presented as follows:

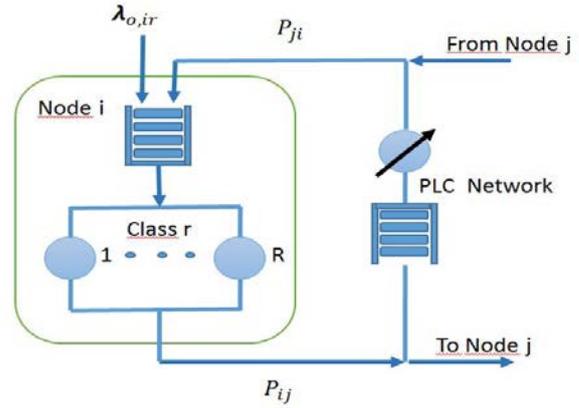


Fig. 10. Model for Node  $i$

- a.  $S_{ir}$  is the service status in the node  $i$  and class  $r$ , which can take values of 0 or 1 for the OFF and ON states respectively. From this criterion, the probability that a service will be active in the node  $i$  and class  $r$  can be expressed with (59):

$$P_{S_{ir}} = \frac{S_{ir}}{\sum_{i=1}^N \sum_{r=1}^R S_{ir}} \quad (59)$$

- b. Considering a uniform distribution, the expression that allows calculating the probability that a packet can be transmitted from node  $i$  to node  $j$  in a network with  $N$  nodes is given by (60):

$$P_{t_{ij}} = \frac{1}{N} \quad (60)$$

- c. To estimate the probability that a packet of class  $r$  is sent from node  $i$  to node  $j$ , it must be considered that both nodes have a state service of class  $r$  in state On. On the basis of the above, the probability that a class  $r$  packet can be sent from node  $i$  to node  $j$  can be calculated in this way (61) (62):

$$P_{ij,r} = P_{ji,r} = P_{t_{ij}} \cdot P_{S_{ir}} \cdot P_{S_{jr}} \quad (61)$$

$$P_{ij} = \sum_{r=1}^R P_{ij,r} \quad (62)$$

A summary of the expressions per node and per class, which allows calculating the probabilities of arrival and departure of packets to the PLC network, is presented below.

Per node	Per class
$\lambda_{0,i}$ :Arrival rate of	$\lambda_{0,ir}$ :Arrival rate of a
packets from outside the	packet from outside the

network to the node $i$ .	node $i$ class $r$
$\lambda$ : Total arrival rate of packets from outside to an open network.	
$\lambda = \sum_{i=1}^N \lambda_{0,i} = \sum_{i=1}^N \sum_{r=1}^R \lambda_{0,ir} \quad (63)$	
$p_{0,i}$ : Probability that a packet enters from outside to the node $i$ . The node with index 0 (zero) represents the outside world.	
$p_{0,i} = \frac{\lambda_{0,i}}{\lambda} \quad (64)$	
$p_{i0}$ : Probability that a packet leaves the network after completing the service at node $i$ .	$p_{ir,0}$ : Probability that a packet of class $r$ from node $i$ leaves the network.
$p_{i0} = 1 - \sum_{j=1}^N p_{ij} \quad p_{ir,0} = 1 - \sum_{j=1}^N \sum_{s=1}^R p_{ij,s}$	

### 3. RESULTS AND DISCUSSION

#### 3.1 Proposed scenario: saturated channel status under multiclass traffic conditions

Figure 11 shows the corresponding scheme of the proposed scenario of a Home Area Network (HAN) composed of eight (8) nodes PLC. Each node consists of a PLC adapter and a traffic source. Each source of traffic can generate more than one class of traffic  $r$  simultaneously (Voice, Data, Video and Telemetry). Node 8 will be considered as a primary node or Coordinator (CCo). Table 2 presents the traffic classes are and the codec set (applicable only to Voice or Video) for each the node  $i$  and class  $r$  that are part of the proposed scenario.

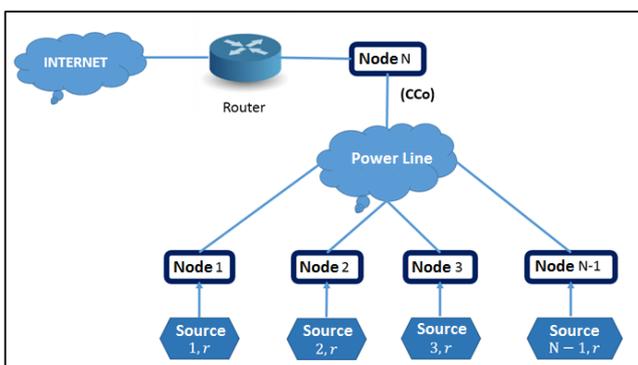


Fig. 11. Practical scenario of a multiservice network on PLC

Table 2. Traffic classes per the node  $i$  and class  $r$  scenario 4

Node $i$	Traffic classes			
	Voice ( $r=1$ )	Video ( $r=2$ )	Control ( $r=3$ )	Data ( $r=4$ )
1	G.711		X	X
2	G.723.1		X	X
3		MPEG-4		X
4	G.729		X	X
5		MPEG-2	X	
6				X
7	G.711			X
8(CCo)	X	X	X	X

Table 3 presents the BW required for each traffic class for the proposed scenario.

Table 3. BW required for each node  $i$  and class  $r$  scenario 4

Node $i$	Traffic classes			
	Voice [kbps]	Video [Mbps]	Control [kbps]	Data [Mbps]
1	81,6		1,5	3,5
2	23,2		2,2	10,2
3		18,4		8,4
4	35,8		2,7	12,7
5		15,38	1,8	
6				16,5
7	102,6			11,6
8(CCo)	243,2	33,78	8,2	62,9

The tool called "Generator Channel  $PLC$  ( $GC\_PLC$ )" is used to calculate the value of  $BW_T$ , it is written in MATLAB and developed by Dr. Francisco Javier Cañete (Ph.D), who belongs to the PLC Group of the University of Malaga-Spain.  $GC\_PLC$  allows estimating the behavior of a PLC channel, according to the parameters associated with the topology of a PLC network, in a typical residential environment. In addition, the tool performs an evaluation process of the channel below the band of 30MHz, because the PLC network adapters operate in this frequency band under the HPAV standard. In [14] all the information is presented for using the tool  $GC\_PLC$ .

The tool  $GC\_PLC$  generated the next values: 159.72 Mbps, 120.65 Mbps and 83.58Mbps; which correspond to the capacity that may be present in a PLC channel under a channel condition: Excellent, regular (Typical) and Deficient respectively

According to the values shown in Table 3, the total BW required by HAN network is 193.86 Mbps, which is greater than the total channel capacity PLC in any of the three channel conditions suggested,

which establishes a state of saturation of the PLC channel.

There is an important aspect to be considered on the proposed scenario, it is to consider the criterion that the CCo node is directly connected to the router that allows the HAN network output to Internet and on which it circulates most of the traffic, under the assumption that most of the services depend on Internet.

### 3.2 Comparative analysis between SM-HPAV and HM-HPAV

The proposed scenario was considered in order to make a comparative analysis between the SM-HPAV and HM-HPAV, which has a saturated

channel with a multiclass traffic and it is under excellent, typical and deficient channel conditions. The main objective is to evaluate the Throughput, delay and efficiency parameters for each one of the models. Only the values of the BW assigned by using the Shapley value were considered in the test. The results obtained for each of the models are in Tables 4, 5 and 6. It is important to take into account that in the process of analysis were only taken the mechanisms of access [CSMA / CA, TDMA and OFDMA] due to the particularity of the PLC technology.

Table 4. Throughput, delay and efficiency by model for an excellent state of the channel

Channel state: Excellent				MS-HPAV			MH-HPAV		
Session	CoS	BW Request [Mbps]	BW Assigned (Shapley) [Mbps]	Throughput [Mbps]	Delay [ms]	Efficiency %	Throughput [Mbps]	Delay [ms]	Efficiency %
1	Voice	0,0816	0,058	0,05560	48,90	68,14	0,07037	36,10	86,24
2		0,0232	0,0167	0,01554	47,40	66,99	0,02001	36,10	86,24
3		0,0358	0,0259	0,02540	47,00	70,96	0,03087	36,10	86,24
4		0,1026	0,0741	0,07024	48,70	68,46	0,08848	36,10	86,24
5		0,2432	0,2233	0,20628	39,30	84,82	0,20973	36,10	86,24
6	Video	18,4	13,7348	11,85953	51,70	64,45	8,60885	446,10	46,79
7		15,38	11,1597	9,63600	53,20	62,65	8,60885	329,20	55,97
8		33,78	31,0153	26,76746	42,10	79,24	8,60885	1041,90	25,49
9	Control	0,0015	0,0011	0,00102	47,80	67,81	0,00047	33,30	31,69
10		0,0022	0,0016	0,00153	48,90	69,41	0,00069	33,30	31,00
11		0,0027	0,002	0,00198	48,30	73,41	0,00084	33,30	31,48
12		0,0018	0,0013	0,00127	48,10	70,53	0,00057	33,30	31,47
13		0,0082	0,0075	0,00681	37,90	83,07	0,00258	33,30	31,08
14	Data	3,5	2,487	2,15750	54,10	61,64	1,12683	36,50	31,17
15		10,2	7,3497	6,33994	53,60	62,16	3,19534	41,90	31,54
16		8,4	6,2702	5,40859	51,80	64,39	2,72341	40,70	32,18
17		12,7	9,1822	7,93389	53,40	62,47	4,06700	44,50	32,08
18		16,5	11,982	10,35026	53,10	62,73	5,34571	47,80	31,03
19		11,6	8,3769	7,23232	53,50	62,35	3,74860	43,30	32,43
20		62,9	57,7519	49,81333	42,10	79,19	19,58467	85,30	31,68
<b>Total</b>		<b>193,8628</b>	<b>159,721</b>						

Table 5. Throughput, delay and efficiency by model for a typical state of the channel

Channel state: Típical				MS-HPAV			MH-HPAV		
Session	CoS	BW Request [Mbps]	BW Assigned (Shapley) [Mbps]	Throughput [Mbps]	Delay [ms]	Efficiency %	Throughput [Mbps]	Delay [ms]	Efficiency %
1		0,0816	0,0449	0,04344	62,60	53,24	0,07037	36,10	86,24
2		0,0232	0,0128	0,01240	67,10	53,43	0,02001	36,10	86,24
3		0,0358	0,0197	0,01941	61,50	54,22	0,03087	36,10	86,24
4		0,1026	0,0566	0,05431	63,00	52,94	0,08848	36,10	86,24
5		0,2432	0,1699	0,15098	53,70	62,08	0,20973	36,10	86,24
6	Video	18,4	9,8756	8,52681	71,90	46,34	6,50299	677,20	35,34
7		15,38	8,43	7,27188	70,50	47,28	6,50299	524,10	42,28
8		33,78	23,5972	20,35110	55,30	60,25	6,50299	1365,10	19,25

9	Control	0,0015	0,0008	0,00076	62,80	50,49	0,00035	33,30	23,66
10		0,0022	0,0012	0,00118	67,10	53,61	0,00052	33,30	23,60
11		0,0027	0,0015	0,00141	66,10	52,18	0,00065	33,30	24,19
12		0,0018	0,001	0,00097	65,20	54,07	0,00043	33,30	23,70
13		0,0082	0,0057	0,00532	48,50	64,93	0,00195	33,30	23,73
14	Datos	3,5	1,9253	1,66315	70,10	47,52	0,85156	38,80	24,33
15		10,2	5,6429	4,88985	69,50	47,94	2,48715	49,60	24,38
16		8,4	4,5084	3,89265	71,90	46,34	2,00916	46,70	23,92
17		12,7	6,9928	6,04841	70,00	47,63	2,96579	54,80	23,35
18		16,5	9,028	7,79366	70,60	47,23	3,97853	63,20	24,11
19		11,6	6,3954	5,52721	69,90	47,65	2,76219	51,60	23,81
20		62,9	43,9392	37,89572	55,30	60,25	15,25656	136,80	24,26
<b>Total</b>		<b>193,8628</b>	<b>120,649</b>						

Table 6. Throughput, delay and efficiency by model for a deficient state of the channel

Channel state: Deficient				MS-HPAV			MH-HPAV		
Session	CoS	BW Request [Mbps]	BW Assigned (Shapley) [Mbps]	Throughput [Mbps]	Delay [ms]	Efficiency %	Throughput [Mbps]	Delay [ms]	Efficiency %
1	Voz	0,0816	0,0386	0,03752	72,50	45,98	0,07037	36,10	86,24
2		0,0232	0,011	0,01037	72,80	45,81	0,02001	36,10	86,24
3		0,0358	0,017	0,01678	71,10	46,88	0,03087	36,10	86,24
4		0,1026	0,0488	0,04709	72,60	45,89	0,08848	36,10	86,24
5		0,2432	0,093	0,08701	93,20	35,78	0,20973	36,10	86,24
6	Video	18,4	8,9741	7,75344	79,10	42,14	4,50493	1094,80	24,48
7		15,38	7,3611	6,34842	80,70	41,28	4,50493	872,10	29,29
8		33,78	12,9131	11,14570	101,00	32,99	4,50493	2233,60	13,34
9	Control	0,0015	0,0007	0,00067	76,80	43,38	0,00024	33,30	16,30
10		0,0022	0,001	0,00100	74,80	44,53	0,00037	33,30	16,79
11		0,0027	0,0013	0,00126	69,50	47,98	0,00044	33,30	16,20
12		0,0018	0,0009	0,00088	72,10	46,26	0,00030	33,30	16,70
13		0,0082	0,0031	0,00285	92,90	35,90	0,00138	33,40	16,83
14	Datos	3,5	1,6557	1,43660	81,20	41,05	0,58729	46,40	16,78
15		10,2	4,8459	4,19468	81,00	41,12	1,67989	74,30	16,47
16		8,4	4,0969	3,53525	79,20	42,09	1,39363	66,80	16,59
17		12,7	6,0367	5,20922	81,30	41,02	2,12016	81,20	16,69
18		16,5	7,921	6,84179	80,40	41,47	2,68736	95,70	16,29
19		11,6	5,5132	4,76820	81,10	41,11	1,91350	75,80	16,50
20		62,9	24,0448	20,76082	101,00	33,01	10,39477	283,40	16,53
<b>Total</b>		<b>193,8628</b>	<b>83,578</b>						

The following assumptions are proposed in order to evaluate if the SM-HPAV provides better results than HM-HPAV:

*Throughput Evaluation*

$$H_o: \mu_{Thr\_MH} \leq \mu_{Thr\_MS}$$

$$H_a: \mu_{Thr\_MH} > \mu_{Thr\_MS}$$

Where  $\mu_{Thr\_MH}$  and  $\mu_{Thr\_MS}$  are the Throughput value that was obtained when using HM-HPAV and SM-HPAV respectively. The  $H_o$  hypothesis states that SM-HPAV provides better results than the HM-HPAV, introducing a value of throughput average higher than the current method and the  $H_a$  establishes the contrary condition.

*Delay Evaluation*

$$H_o: \mu_{R\_MS} \leq \mu_{R\_MH}$$

$$H_a: \mu_{R\_MS} > \mu_{R\_MH}$$

Where  $\mu_{R\_MH}$  and  $\mu_{R\_MS}$  correspond to the average delay obtained when using HM-HPAV and SM-HPAV respectively. The  $H_o$  hypothesis states that SM-HPAV provides better results than HM-HPAV, introducing a delay average lower than the current method and the  $H_a$  establishes the contrary condition.

*Efficiency Evaluation*

$$H_o: \mu_{\eta\_MH} \leq \mu_{\eta\_MS}$$

$$H_a: \mu_{\eta\_MH} > \mu_{\eta\_MS}$$

Where  $\mu_{\eta_{MH}}$  and  $\mu_{\eta_{MS}}$  correspond to the average efficiency when using HM-HPAV and SM-HPAV respectively. The  $H_o$ , hypothesis suggests that the Smart Model provides better results than the Hybrid Model, introducing a average efficiency higher than the current method and the  $H_a$  establishes the contrary condition.

It is necessary to make a contrast of hypothesis about mean difference with paired

sampling using the paired t-test to accept or reject each of the hypotheses that have been raised. *MiniTab* statistical software and the recorded values in Tables 4, 5 and 6 were used. The result obtained in each of the tests is consolidated in Table 7:

Table 7. Paired-t test results for each of the hypotheses established

Variable	$H_o$	Degrees of freedom	Statistical	Range of acceptance $\{t: t < T_{(\alpha, n-1)}\}$	$H_o$ is accepted
Throughput	$\mu_{Thr_{MH}} \leq \mu_{Thr_{MS}}$	59	-3,769	$(-\infty, 1.6711)$	Sí
Delay	$\mu_{R_{MS}} \leq \mu_{R_{MH}}$	59	-2.408	$(-\infty, 1.6711)$	Sí
Efficiency	$\mu_{\eta_{MH}} \leq \mu_{\eta_{MS}}$	59	-3.880	$(-\infty, 1.6711)$	Sí

Table 7 shows that the statistical value for each one of the cases is within the acceptance interval, so  $H_o$  is accepted in all of the three cases. In view of the above, it is concluded that SM-HPAV is better than HM-HPAV, considering that for the proposed scenario and under different traffic classes SM-HPAV allows improving the levels of throughput, delay and efficiency compared to MH -HPAV with 95% of reliability.

On the other hand, Table 8 shows a comparative table of Throughput, Delay and Efficiency variables for SM-HPAV and HM-HPAV models based on the average value and the percentage of difference.  $V_{MS}$  and  $V_{MH}$  correspond to the resultant value with SM-HPAV and HM-HPAV respectively. According to the results it is important to mention the next details:

- The Throughput value achieved by SM-HPAV exceeds by 108.1% to HM-HPAV, that means that the Throughput levels are doubled with the proposed model from the current state, aspect that significantly improves the transmission processes on Power Line Communications.
- The delay levels are reduced by 65.16% in the SM-HPAV against the HM-HPAV, which is quite favorable for the transmission of voice and video.

Table 8. Comparative table between SM-HPAV and HM-HPAV

Variable	Model	Media	% difference = $\frac{(V_{MS} - V_{MH}) * 100}{V_{MH}}$
Throughput	MS-HPAV	5,237	108,103
	MH-HPAV	2,517	
Delay	MS-HPAV	64,630	-65,160
	MH-HPAV	185,505	
Efficiency	MS-HPAV	54,503	33,456
	MH-HPAV	40,840	

- The SM-PDCA improves the efficiency of the current system in 33.45% which may be considered an aspect of vital importance because a solution to the proposed problem is provided by optimizing the allocation of resources and providing adequate levels of QoS to each one of the nodes that are part of the PLC network

#### 4. CONCLUSIONS

Thanks to the results of this investigation it was possible to demonstrate that the cooperative game theory can be considered as a very important

strategy when it is equitably distributed the capacity of a PLC channel among all nodes that are part of the network, in order to optimize the resource allocation. This is achieved for the established requirements per each node, providing adequate levels of QoS and significantly improving the throughput, delay and efficiency levels, compared with the current conditions of the PLC technology, with a confidence level of 95%. In addition, when considering the nodes of a network as players who can work cooperatively, the probability of getting a higher profit against the one obtained before when acting individually.

One aspect that can be considered as a great contribution to the study of PLC technology, is the proposed model  $M^R/M/1/B$ , supported in a scheme "Weighted Round Robin Scheduler (WRR)" as a strategy to represent and evaluate the performance of a PLC network, under a multiuser-multiclass context, using OFDMA as a mechanism of media access in residential environments. The model allows estimating various performance parameters and evaluating the performance of each one of the services required by each node; by using the cooperative game theory of transferable utility, maximizing the bandwidth and reducing the levels of delay in each node. This favors the development of future projects related to the use of PLC technology in residential environments, considering that until this moment there is not a capable model that represents this type of scenario, supported in the HPAV standard.

Another contribution that was proposed in the article is the HM-HPAV model which evaluates the performance of a PLC network according to the current state of the HPAV technology, using CSMA/CA and TDMA as media access mechanisms, based on a WRR and RR scheme respectively. An important element of the proposed model was the inclusion of scheme called AFR (Aggregation With Fragment Retransmission), in which the information is divided into multiple blocks (PB) with constant length ( $PB_{size}$ ), for subsequent transmission in only one frame of larger length, retransmitting only the corrupt fragments that failed the approval by the receptor. This scheme had not been considered by any of the proposed models for HPAV by other authors, so it allows to represent the behavior of the PLC technology in a more accurately way.

The use of OFDMA as a multiplexing technique was considered for the proposed model SM-HPAV, which is known as the multiuser version of OFDM, where multiple nodes can share the spectrum of a channel by distributing resources both in frequency

and in time, in order to optimize the network performance, thereby ensuring different levels of QoS depending on the allocated bandwidth. As a result of this process, the model requires the elaboration of a time and frequency distribution map for a PLC channel on OFDMA, in which the 917 subcarriers are distributed in subchannels  $m$  which are formed by an equitable neighborhood frequencies and on the other hand, the adopted period by HPAV (33,33ms), equivalent to two cycles of a 60Hz network, distributed in 813 timeslots, according to the time of an OFDM symbol ( $T_s = 40,96\mu s$ ) for the particular case of HPAV. Being coherent with the obtained results, it was shown that on the proposed map the CCO should elaborate a (Scheduler) for resource allocation in time and frequency for each node, depending on the channel conditions, the network topology, the number of stations, the traffic intensity by class and the bandwidth; supported by the cooperative game theory of transferable utility. That aspect could be addressed in future research.

#### References

- [1] H. Latchman, K. Srinivas, L. Yonge, and S. Gavette, *Homeplug AV and IEEE 1901: A Handbook for PLC Designers and Users*, 1a ed. New Jersey, USA: Wiley-IEEE Press, 2013.
- [2] Y. Lee, H. a. Latchman, H. Ha, and M. Hwang, "QoS augmented CSMA/CA MAC protocol for high speed multimedia powerline communications," *2012 IEEE Int. Symp. Power Line Commun. Its Appl.*, pp. 236–241, Mar. 2012.
- [3] and V. V. Chatzimisios, P., Anthony C. Boucouvalas, "Performance analysis of the IEEE 802.11 MAC protocol for wireless LANs," *International J. Commun. Syst.*, vol. 18, no. 6, pp. 545–569, 2005.
- [4] Min Young Chung, Myoung-Hee Jung, Tae-Jin Lee, and Yutae Lee, "Performance analysis of HomePlug 1.0 MAC with CSMA/CA," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 7, pp. 1411–1420, Jul. 2006.
- [5] P. J. Piñero-Escuer, J. Malgosa-Sanahuja, and P. Manzanares-Lopez, "Homeplug-AV CSMA/CA Evaluation in a Real In-Building

- Scenario,” *IEEE Commun. Lett.*, no. June, pp. 683–685, 2011.
- [6] S.-G. Yoon, J. Yun, and S. Bahk, “Adaptive Contention Window Mechanism for Enhancing Throughput in HomePlug AV Networks,” in *Consumer Communications and Networking Conference, 2008. CCNC 2008. 5th IEEE*, 2008, pp. 190–194.
- [7] P. J. Pinero-Escuer, J. Malgosa-Sanahuja, P. Manzanares-Lopez, and J. P. Munoz-Gea, “Homeplug-AV CSMA/CA Cross-Layer Extension for QoS Improvement of Multimedia Services,” *IEEE Commun. Lett.*, vol. 18, no. 4, pp. 704–707, Apr. 2014.
- [8] T. Li, “Improving Performance for CSMA/CA Based Wireless Networks,” National University of Ireland, 2007.
- [9] F. Gebali, *Analysis of Computer and Communication Networks*. Springer, 2008.
- [10] P. C.-H. Ng and P. S. Boon-Hee, *Queueing Modelling Fundamentals: With Applications in Communication Networks*. John Wiley & Sons, 2008.
- [11] D. Kurzyk and P. Gawron, *Quantum Queuing Networks Throughput Optimisation*. Springer International Publishing, 2014.
- [12] C.-H. Ng and S. Boon-Hee, *Queueing modelling fundamentals: With applications in communication networks*, 2a ed. West Sussex, Inglaterra: John Wiley & Sons, 2008.
- [13] M. J. Neely, *Stochastic Network Optimization with Application to Communication and Queueing Systems*. Morgan & Claypool Publishers, 2010.
- [14] F. Canete, “User guide for PLC channel generator v. 2,” Universidad de Málaga, 2011.
- [15] N. Anatory, J. & Theethayi, *Broadband Power-Line Communication Systems: Theory and Applications.*, 1a ed. Southampton, England: WIT Press, 2010.
- [16] M. Zimmerman and K. Dostert, “The Low Voltage Power Distribution Network as Last Mile Access Network—Signal Propagation and Noise Scenario in the HF-Rang,” ... *J. Electron. Commun.*, vol. 51, no. 1, pp. 13–22, 2000.
- [17] C. Y. Guillen, E. P., López, J. J., & Barahona, “Throughput Analysis over Power Line Communication Channel in an Electric Noisy Scenario.,” *Proc. World Acad. Sci. Eng. Technol.*, vol. 45, 2008.
- [18] I. Curiel, *Cooperative game theory and applications: cooperative games arising from combinatorial optimization problems*. Dordrecht: Kluwer Academic Publishers, 1997.
- [19] M. E. Febles, “Sistema de reparto de poder en las elecciones locales,” *Números*, vol. 39, pp. 13–20, 1999.
- [20] S. Bannister and P. Beckett, “Enhancing powerline communications in the ‘Smart Grid’ using OFDMA,” in *Power Engineering Conference, 2009. AUPEC 2009. Australasian Universities*, 2009, pp. 1–5.
- [21] D. Zhang, Y. Wang, and J. Lu, “QoS aware relay selection and subcarrier allocation in cooperative OFDMA systems,” *IEEE Commun. Lett.*, vol. 14, no. 4, pp. 294–296, Apr. 2010.
- [22] X. Huang and B. Bensaou, “On max-min fairness and scheduling in wireless ad-hoc networks: analytical framework and implementation,” *Proc. 2nd ACM Int. Symp. Mob. ad hoc Netw. Comput.*, 2001.
- [23] A. Magaña, “Formación de coaliciones en los juegos cooperativos y juegos con múltiples alternativas. Thesis PhD,” Universidad Politécnica de Cataluña, 1996.
- [24] J. García, “Complejidad y algoritmos en juegos cooperativos. Thesis PhD,” Universidad de Sevilla, 2000.
- [25] K. Ríbnikov, *Análisis Combinatorio*. Moscú: Editoria Mir, 1988.

- [26] I. Mann and L. S. Shapley, “Values of Large Games, VI.” RAND Corporation, 1962.
- [27] J. C. Vesga, G. Granados, and J. E. Sierra, “El valor de shapley como estrategia de optimización de recursos sobre Power Line Communication (PLC).,” *Ing. y Cienc.*, vol. 11, no. 22, pp. 189–211, 2015.
- [28] V. Iversen and B. Sanders, “Engset formulæ with continuous parameters—theory and applications,” *AEU-International J. Electron. Commun.*, vol. 55, no. 1, pp. 3–9, 2001.