Analysis and improvement of multicast communications in HomePlug AV-based in-home networks

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Abstract

The increasing number of home devices with communication capabilities is propelling the research into new communication technologies for in-home networks. Power Line Communications (PLC) has proven to be a feasible alternative for this purpose, and the Homeplug AV standard has become one of its most popular solutions. However, while multicast communications are demanded by many services commonly used in home scenarios, the Homeplug AV implements an inefficient mechanism in which they are carried out as successive point-to-point transmissions. The aim of this paper is to outline the limitations of such scheme and to propose algorithms that improve the multicast performance of the standard. To this end, we have developed a simulation tool for HomePlug AV-based in-home networks. It implements the physical and MAC layers, as well as traffic models for the most common home network services. One of its distinctive features is the ability to generate PLC channels with similar correlation to the ones established in a given home. This correlation has been traditionally neglected, leading to inaccurate performance estimations and to discard suitable multicast algorithms. The considered multicast schemes are firstly compared in terms of their physical bit rate. Finally, their capacity to

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deliver a video streaming service is assessed.
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1. Introduction

Nowadays there is an increasing number of home devices equipped with communication capabilities. From computers and mobile phones to traditional home appliances, all of them can be interconnected to share information or simply be connected to the Internet through the home access point. For these reasons, home networks (also called in-home networks) have recently attracted a significant interest in both the industry and the scientific community.

Several technologies can be used to deploy a home network, from traditional approaches like wired and wireless technologies, to the recently introduced no-new-wires solutions, which use existing infrastructures at homes to lay out the network. This category includes technologies that use the telephone line, the coaxial cable or the low voltage power grid inside the user premises to exchange data. The disadvantage of the former is that the number of telephone and cable sockets is very limited in most homes outside the US.

In-home power line communications (PLC) networks may provide a large catalogue of services. Many of them require multicast communications, e.g. music and video streaming, online computer gaming, gaming consoles, or even video conferencing. However the most popular PLC standard, HomePlug AV(HomePlug Audio and Video, or simply HPAV) [1], does not implement real multicast data transmission. This is probably due because its bit-loaded OFDM physical layer has been designed to exploit the frequency selectivity of the channel, which is a very link dependent feature. Therefore, multicast transmissions in HPAV networks are implemented as a set of consecutive point-to-point transmissions that are carried out in a transparent way to end users.

The multicast problem has been widely explored in wireless scenarios, and some solutions have been recently proposed. They can be divided into two categories, solutions that try to minimize the total power consumption under the fixed system throughput constraint [2][3], and solutions that maximize the total system throughput under the power consumption constraint [4][5][6]. However, these results cannot be directly applied to PLC, since the maximum power spectral density (PSD) is the most restrictive constraint in this technology. In fact, all carriers are usually transmitted at the maximum power level allowed by the PSD mask. Hence, decreasing the power level used in one carrier does not allow increasing it in another one. Therefore, the contributions to this area in PLC networks are very limited. To the authors' best knowledge, the only relevant contribution related to multicast communications in these networks can be found in [7], where the use of pre-coded OFDM is proposed. This solution improves the multicast throughput but requires significant changes at the physical layer, which discards it as a real alternative for the HPAV standard. Moreover, these works only evaluate the physical layer transmission rates, but do not consider their implications at higher layer services.

A common feature of the aforementioned multicast works is that they have been accomplished in wireless scenarios or using PLC channel models that generate uncorrelated channels. Nevertheless, all the links established in a given in-home PLC network share a common network layout, which causes the channels to exhibit some degree of correlation. This correlation has been traditionally neglected because it has no influence on the physical layer analysis in point-to-point communications. However, it cannot be disregarded when assessing multicast algorithms, since their performance is strongly dependent on the differences among the involved channels. The larger the dissimilarities among them, the poorer the multicast performance.

In this context, we make three main contributions:

- We present a PLC simulator based on the HPAV standard that takes into account the correlation among the channels established in the same in-home network. It implements the physical and MAC layers, as well as traffic models for the most common home network services. Channel responses are obtained using a bottom-up model in which a simplified random topology is generated for each in-home network. Hence, the user is released from the burden task of defining the grid layout. However, since all the links established in this network share some layout elements, the resulting channels will exhibit a similar degree of correlation to the actual ones.

- We evaluate the multicast performance of the HPAV. We show that it can be significantly improved even by means of the classical multicast algorithm in which the number of bits per carrier is determined by the user with the worst signal to noise ratio (SNR). In addition, a more elaborated multicast algorithm is proposed for scenarios with higher number of users.
- We assess the performance of a video streaming service using the multicast strategy implemented in the HPAV standard and a modified version that includes the classical multicast algorithm.

The remainder of the paper is structured as follows. In section 2, the different multicast protocols considered in this paper are described. Then, in section 3 a brief description of the simulation environment is presented and the performance evaluation results are shown in section 4. Finally, section 5 concludes the paper.

2. Multicast communications algorithms

2.1. Multicast communications in the HPAV standard

The PLC medium exhibits remarkable variations among locations. The characteristics of the communication links depend on the network topology, the type of wires and the connected loads. Even in a specific in-home network, significant differences in the characteristics of the links can be found depending on the selected transmission path or the status of the electrical appliances. In order to adapt the physical layer modulation to this medium, the HPAV standard uses an OFDM modulation with $N = 917$ useful carriers in the 2-28 MHz frequency band. Each of these carriers can be independently modulated from a simple BPSK constellation (one bit of information per symbol) to 1024 QAM (ten bits of information per symbol). Since the channel characteristics among each transmitter-receiver pair are different, so do the used constellations.

In order to send a multicast frame to a multicast group, the current version of the HPAV standard sends one point-to-point frame to each member of the multicast group. This technique clearly degrades the performance of multicast services as the number of receivers increases. Its effective multicast transmission bit rate can be calculated by means of expression (1). Since transmissions are serially accomplished, the time required to accomplish the multicast transmission, T_M, is the sum of the transmission times of the M multicast clients, t_m, with $m = 1...M$. Therefore, assuming that the transmitted data has size L, and that the channel conditions remain invariable during the transmissions, the inverse of the multicast bit rate, C_M, will be the sum of the inverse of the different clients bitrates, C_m.

$$T_M = \sum_{m=1}^{M} t_m \Rightarrow C_M = \frac{L}{T_M} = \frac{L}{\sum_{m=1}^{M} t_m} \Rightarrow \frac{1}{C_M} = \frac{\sum_{m=1}^{M} t_m}{L} = \sum_{m=1}^{M} \frac{1}{C_m} \quad (1)$$

It will be shown in this paper that this poor performance can be improved even with a multicast algorithm that selects a common tone map for all the multicast clients. This is the most straightforward multicast strategy and will be referred to as Greatest Common Tonemap (GCT). Although its performance in PLC networks is much better than in wireless environment, it still decreases more rapidly than in other strategies when the number of user increases. A new algorithm is proposed to tackle situations with a relatively high number of users, e.g., in a hotel floor. This algorithm will be referred to as Aggregated Multicast Bit rate Maximization (AMBM).

2.2. Greatest Common Tonemap (GCT)

In this technique, the constellation used in each carrier will be that of the multicast user with the worst SNR in the corresponding frequency band. Let us denote by $b_{m,k}$ the number of bits per symbol that the mth user would use in carrier k in a single-user scenario. The number of bits per multicast symbol in carrier k, b_k, is computed as

$$b_k = \min_m (b_{m,k}) \quad \text{for } m = 1...M, \tag{2}$$

and the multicast bit rate is

$$C_M = \frac{1}{T} \sum_{k=1}^{N} b_k, \tag{3}$$

where T is the OFDM symbol period.

This algorithm is implemented at the physical layer and could be added to the HPAV standard with minimum changes. It is the simplest multicast algorithm and has been widely evaluated in wireless networks with quite poor performance [4]. Because of this fact, it has been traditionally discarded also for PLC. However, in contrast to wireless network, where users experience independent fading, channel responses in a given PLC network exhibit significant correlation among them. This reduces the differences among the SNR experienced by different users in a given subband. As a consequence, the performance of the algorithm is significantly better than in scenarios where channels from different users are uncorrelated. To the authors' best knowledge, this fact has not been previously considered in the literature.

2.3. Aggregated Multicast Bit rate Maximization (AMBM)

The objective of this algorithm is to maximize the aggregated multicast bit rate at the physical layer. This is done at the expense of achieving a different bit rate for each multicast user. Therefore, retrieving information in these circumstances requires the use of some kind of coding in higher layers, which will be discussed at the end of this section. Hence, the suitability of this algorithm for PLC will depend on the trade-off between the gain achieved at the physical layer and the overhead introduced by the selected coding technique. Since the bit rate gain at the physical layer (with respect to the GCT) increases with the number of users, this strategy will be useful in scenarios with high number of users.

The aggregated multicast bit rate can be improved by solving the optimization algorithm shown in expression (4). The function $\rho_{m,k}$ indicates whether the mth client will use carrier k, $\rho_{m,k} = 1$, or not, $\rho_{m,k} = 0$, in the multicast transmissions. It is the responsible for each multicast user to have a different physical bit rate.

$$\max \sum_{m=1}^{M} \sum_{k=1}^{N} b_k \cdot \rho_{m,k}$$
$$\text{subject to } \; b_k = \min_{m}(b_{m,k} \cdot \rho_{m,k}) \;\; \forall \rho_{m,k} = 1, m = 1...M. \tag{4}$$

In this case, it is difficult to obtain a unique multicast bit rate value in order to compare it with the previous algorithms, because the algorithm assigns a different bit rate for each multicast user. In this paper, we consider that the multicast bit rate (C_M) can be computed as the average amount of multicast information delivered in a given time period,

$$C_M = \frac{1}{MT} \sum_{m=1}^{M} \sum_{k=1}^{N} b_k \cdot \rho_{m,k}, \tag{5}$$

which is larger than (1) and (3), as it will be shown later in this paper.

The optimization problem stated in (4) is a nonlinear integer programming one with NP-hard complexity. It has $(B \cdot M)^N$ possible solutions, where B is the number of different values that b_k might take, i.e. the number of different constellations. The following greedy algorithm is proposed to solve it.

For $k = 1...N$ do:

1. Sort the values of $b_{m,k}$, deleting duplicated elements. The resulting list, $\mathbf{r}$, represents all the possible values that can be assigned to b_k.
2. For each element $r_i \in \mathbf{r}$, calculate the sum of the number of bits per symbol that the different clients would obtain in the considered

carrier if r_i is finally used as the number of transmitted bits. This magnitude can be denoted by B_k and is obtained by multiplying r_i by the number of clients with $b_{m,k} >= r_i$, which is denoted by $N(r_i)$. It should be taken into account that $\rho_{n,k} = 0$ if $r_i > b_{m,k}$, i.e., the mth client will not use carrier k.

3. Select the value of r_i that provides the highest B_k.

An example is given below to illustrate the procedure. For simplicity, only three carriers, denoted as k_0, k_1, k_2, are considered in an scenario with $M = 4$ clients. The single-user tone map of the different users are $b_{1,k} = [3, 4, 6]$, $b_{2,k} = [6, 5, 9]$, $b_{3,k} = [6, 2, 7]$, $b_{4,k} = [9, 5, 9]$. Hence, for k_0, $\mathbf{r} = [3, 6, 9]$ and the following results are obtained when the second and third steps of the algorithm are executed,

- $r_1 = 3 \Rightarrow B_{k_0} = 3 \cdot N(3) = 3 \cdot 4 = 12$,
- $r_2 = 6 \Rightarrow B_{k_0} = 6 \cdot N(6) = 6 \cdot 3 = 18$,
- $r_3 = 9 \Rightarrow B_{k_0} = 9 \cdot N(9) = 9 \cdot 1 = 9$.

Since the highest bit rate is achieved when client 1 does not use carrier k_0, it results that $\rho_{m,k_0} = [0, 1, 1, 1]$. The number of bits that the clients would extract from each multicast symbol is $b_{n,k_0} \cdot \rho_{m,k_0} = [0, 6, 6, 6]$.

In the same way, for k_1, the obtained results are:

- $r_1 = 2 \Rightarrow B_{k_1} = 2 \cdot N(2) = 2 \cdot 4 = 8$,
- $r_2 = 4 \Rightarrow B_{k_1} = 4 \cdot N(4) = 4 \cdot 3 = 12$,
- $r_2 = 5 \Rightarrow B_{k_1} = 5 \cdot N(5) = 5 \cdot 2 = 10$.

Therefore, $b_{n,k_1} \cdot \rho_{m,k_1} = [4, 4, 0, 4]$. Finally, using the same procedure, $b_{n,k_2} \cdot \rho_{m,k_2} = [6, 6, 6, 6]$. With these results, the number of bits per symbol obtained for each client is:

- $b_{1,k} = [0, 4, 6] = 10$,
- $b_{2,k} = [6, 4, 6] = 16$,
- $b_{3,k} = [6, 0, 6] = 12$,
- $b_{4,k} = [6, 4, 6] = 16$,

If the GCT algoritm is applied in the same scenario, the results would be $b_{1,k} = b_{2,k} = b_{3,k} = b_{4,k} = [3, 2, 6] = 11$. As expected, with the AMBM algorithm the clients with the best channel conditions obtain better results at the expense of reducing the bitrate of clients with bad conditions. This is in contrast to the results obtained with the GCT algorithm, where all the clients obtain the same bitrate to the detriment of clients with good SNR. On the other hand, the AMBM algorithm usually leads to different physical bit rates for each multicast client. As a consequence, a higher layer coding must be used to manage this asymmetry. Different alternatives can be used to this end, but the most well-known are the MDC (Multiple Description Coding) [8] and the Fountain codes [9].

MDC is a source coding technique used to separate a media stream into multiple substream called descriptors. The reception of only one of these descriptors is enough to decode and show the original audio or video but, the more descriptors are received, the highest quality is obtained. The disadvantage of MDC is that it introduces a significant overhead, which for a video source is usually about 44% [10].

On the other hand, the main idea behind Fountain codes is that the transmitter is able to generate a potentially infinite amount of encoded packets from the original data. A receiver will be able to decode a message composed of K packets from any set of K' encoded packets, for K' slightly larger than K. There are different implementations of Fountain Codes, but the most popular nowadays are the Raptor codes [11], which introduce an overhead of about 4-5% [12]. Hence, this seems to be the most suitable alternative to be used in conjunction with the AMBM algorithm.

3. HomePlug AV simulator

The presented multicast techniques have been assessed by means of a realistic simulator of HomePlug AV in-home networks. It implements both the physical and the MAC layers of the standard and is based on the one proposed by the authors in [13]. However, two enhancements have been incorporated into it. The first one relates to the channel model, which has been modified to take into account the correlation among the channels that can be found in a given home network. The second one is that traffic models for the most common services that can be found in in-home communications have been introduced. The structure of the simulator is shown in Fig. 1.

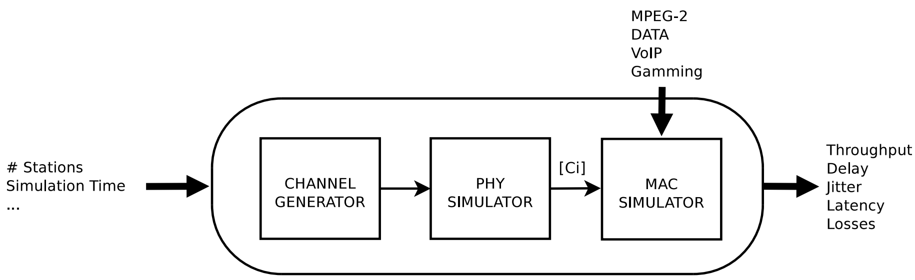


Figure 1: Simulator structure overview

As seen, the simulator consists of three different blocks. The former generates the channel response and the noise for the different stations of the network. Then, the Physical Layer Simulator computes the bit rate, C_i, for each generated channel. Using these values, the MAC layer block simulates the Homeplug AV CSMA/CA protocol with the number of stations and the traffic patterns corresponding to the upper layer services defined as input parameters.

3.1. Channel generator

The channel response generator is based on the simplified bottom-up model proposed in [14]. It considers the indoor power grid as a set of multiple transmission lines interconnected and ended in different impedance values. The link between each pair of stations is represented by a simplified structure consisting on a main path from which three stubs are deployed, as shown in Fig. 2. Similarly, a reduced set of impedance values is considered. This simplified topology is not intended to model the whole layout of the indoor grid, but only the equivalent network seen from the transmitter to the receiver.

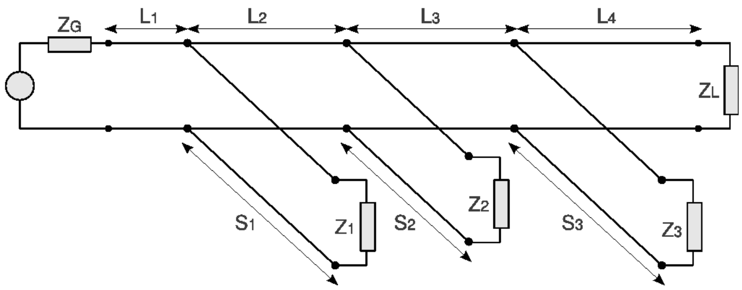


Figure 2: Simplified network topology used by the channel generator. Taken from [14]

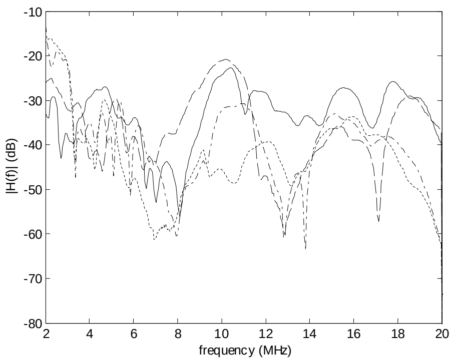
A former version of this generator was implemented in [13]. Nevertheless, the one used in this work includes an important enhancement: it is able to model the correlation existing among the channels established in a given in-home power grid. This is done using the following procedure. The first time the channel response generator is called, it works as the in [13], i.e., the main path, the three stubs length and ending loads are randomly selected. However, channels obtained in successive calls are generated by randomly changing the length of only one of the three stubs and its corresponding impedance value. The changed stub is also randomly selected. Thus, the length of the main path is common for all the channels of an in-home network. In addition, each set of three successive channels also has one common stub length and impedance value.

While the presented strategy causes all the channels of a given network to have similar propagation delays, this does not bias the delay estimations because in-home PLC networks have small size. Hence, the delay is essentially due to the MAC layer (it will be corroborated in section 4.1). On the other hand, the correlation among channels generated with this procedure has proven to be similar to the one exhibited by actual channels measured in 22 indoor networks [15]. As an example, Fig. 3 (a) depicts four channels measured in an apartment, Fig. 3 (b) shows four channels obtained with the proposed generator, and Fig. 3 (c) shows four channels obtained with a generator that does not take into account the correlation among the channels established in a given in-home network. As seen, differences among the channels in Fig. 3 (b) are more realistic than among the channels in Fig. 3 (c). This correlation cannot be achieved by means of any of the statistical channel models proposed in the literature, which generate uncorrelated channels. Compared to other bottom-up models, in which correlation among channels is the natural result of the grid layout, this strategy releases the user from the burden task of defining the in-home grid for each considered network.

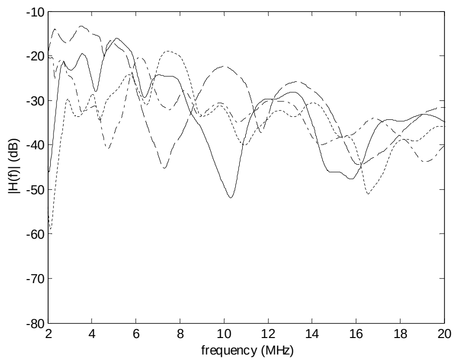
Regarding the Noise Generator, this work uses the one already proposed by the authors in [13]. Noise at each communication end is composed of three terms that are assumed to be stationary: background noise, a set of narrowband interference and two periodic asynchronous impulsive noise components with frequencies 26.3 kHz and 48.9 kHz, respectively. The narrowband interference set consists of 60 AM and 2 FM jammers. Three noise scenarios, which differ in the power of the different noise terms, have been defined: heavily, medium and weakly disturbed.

3.2. PHY layer

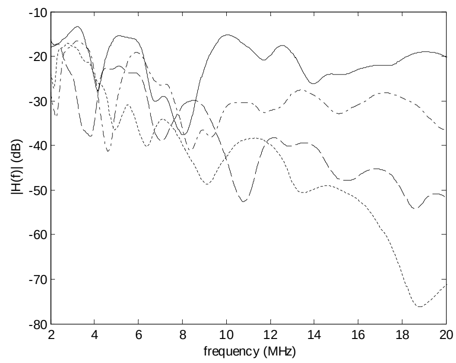
The Physical Layer Simulator implements a pulse-shaped and windowed OFDM system like the one defined in the Homeplug AV standard. It has been already used by the authors in [13]. The system parameters have been drawn from [16][17]. The channel coding block has been substituted by a constant coding gain of 12 dB to speed up simulations, although the corresponding 16/21 code rate is taken into account. The number of bits per carrier is computed subject to an objective bit error rate (BER) of 10^{-5} and under the assumption that both the noise and the intercarrier and intersymbol interference are Gaussian. To compensate for the this approximation, a 3 dB system margin has been



(a) Measured channels



(b) Correlated channels



(c) Uncorrelated channels

Figure 3: Example of measured and generated channels: (a) measured in an apartment, (b) obtained with the proposed channel generator and (c) given by a generator that produces uncorrelated channels

included.

3.3. MAC layer

According to the standard, Homeplug AV provides two services at the MAC layer:

- Connection-oriented contention free service. It is based on a periodic Time Division Multiple Access (TDMA) with dynamic allocation and is intended to support the QoS requirements of demanding applications.
- Connectionless with prioritized contention service based on CSMA/CA. It is used to support both best-effort applications and applications that rely on prioritized QoS.

Since the former is not available in most commercial modems, only the latter has been implemented.

The HomePlug AV CSMA/CA protocol uses priority resolution and random backoff in order to resolve collisions efficiently and to provide QoS. A more detailed analytical description and performance evaluation of this protocol can be found in [17] and [18]. Table 1 shows the values for the protocol parameters considered in this work.

Table 1: HPAV MAC layer parameters.

Parameter	Value	Parameter	Value
max_FL	2501.12 μs	Response Timeout	140.48 μs
RIFS	100 μs	CIFS	30.72 μs
PRS0	35.84 μs	PRS1	35.84 μs
PB Payload	512 bytes	PB Head	8 bytes
Frame Payload	1500 bytes	Frame Head	26 bytes

Fig. 4 depicts an example of the timing sequence for the transmission of frames on the medium. An important restriction on the sequence is the maximum frame transmission time in each channel access (Max_FL), which cannot exceed 2501.12 μs, including the RIFS. Therefore, the amount of bytes transmitted by a station depends on its physical rate. In addition, this quantity must be multiple of the physical block (PB) size.

The receiver selectively acknowledges the PBs and those that are not correctly received are retransmitted during the next channel access of the station. A MAC frame is not considered as received until all of its PBs have been received correctly. Therefore, the lost of a PB turns into a delay growth.

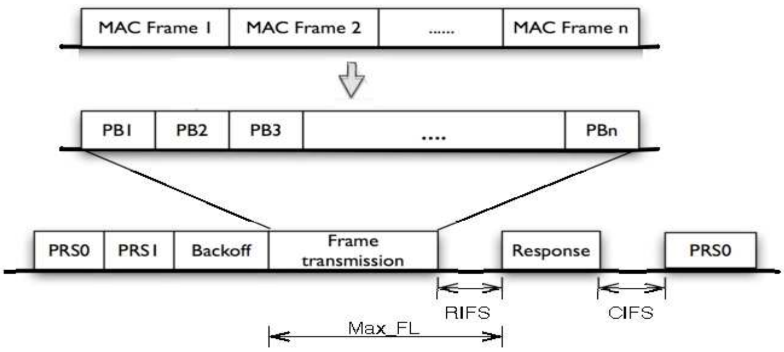


Figure 4: Timing sequence for the transmission of MAC frames

3.4. Upper-layer services

In order to provide an accurate performance evaluation of the mulsticat scenario, the simulator includes traffic models for the services that are commonly used in in-home networks: data transfer, video streaming, VoIP and network gaming. For the sake of brevity, only two of them are used in this work. The following subsections provide a brief description of their main characteristics. It is intended to be accurate but not extensive, since traffic modeling is out of the scope of this paper.

3.4.1. Data transfer

A ON/OFF model has been used to emulate the bursty nature of the TCP-based data transmission. This model uses only two states, namely ON and OFF. The time spent in these states follows an exponential distribution and the stations only transmit data frames during the ON state period.

To select the model parameters for this work, different TCP files transmissions among two isolated HPAV modems were carried out. By analyzing the different sniffer captures, it was obtained that the mean time spent in each state is $6 \cdot 10^{-5}$ and $7.32 \cdot 10^{-4}$ s for OFF and ON states, respectively. Traffic referred to as background in the subsequent sections has been generated according to this model.

3.4.2. Video streaming

Frames to be transmitted are generated according to an MPEG-2 codec model. A typical MPEG-2 encoded video consists of three types of frames, namely as I (intraframe-coded), P (predictive-coded) or B (bidirectionally-predictive-coded) frame. An I-frame is made up of a single uncompressed video frame and its content is unrelated to the one in the preceding and the following frame. On the other hand, P-frames and B-frames use motion-compensated prediction. This prediction is based on the previous frame for P-frames and on the previous and future frames for B-frames. A group of coded frames is called a Group-of-Pictures, or GOP in short. We can choose the way in which the different types of frame occur, referred to as the GOP structure. It can be seen that an I-frame takes more bits for the same quality than a P-frame and, in the same way, a P-frame takes more bits than a B-frame.

The model implemented in this work is based on the one proposed in [19], which suggests a IBBPBBPBBPBBPBB GOP structure. In addition, the size of the different frame types is obtained by using a Lognormal distribution with the parameters shown in table 2. A film is divided into a set of scenes and each scene has a number of GOPs that is exponentially distributed with mean 10. Consecutive I frames in the same scene have exactly the same size of the first I frame. The transmission rate is set to 30 fps.

Table 2: MPEG-2 model Lognormal distribution parameters

Frame type	SDTV Rate	HDTV Rate
I-frame	μ = 800 Kbits σ = 240 Kbits	μ = 3.2 Mbits σ = 960 Kbits
P-frame	μ = 240 Kbits σ = 160 Kbits	μ = 960 Kbits σ = 640 Kbits
B-frame	μ = 80 Kbits σ = 24 Kbits	μ = 24 Kbits σ = 96 Kbits

3.5. Simulator validation

Once the simulator structure has been presented, its validation process is discussed. It has been accomplished in two steps. Firstly, each layer has been individually checked. Then, the overall results given by the simulator are compared with tests carried out with actual HomePlug AV modems.

The testing of each layer is described following a top-down approach. The upper-layer services have been validated by checking that the statistics of the generated traffic correspond to the ones proposed in the models. The MAC layer was validated in a previous work [18], where it was shown that the simulated results fit the analytical values given in [17] for the CSMA/CA algorithm. The testing of the Physical layer has been restricted to assess its performance in AWGN. The reason is that, to the authors' knowledge, available references in the literature evaluate either the overall performance of several layers, e.g. physical and MAC layers, or are restricted to some physical layer blocks, e.g. channel estimator or synchronization algorithm. The Channel Generator comprises two parts: the noise and the channel response. The validation of the noise model is straightforward since most of its components have been taken from measurements. In order to validate the channel response, both the distribution of the channel response parameters and the correlation among the channels of the same network have been compared with those obtained from measurements. The agreement between the generated and the measured distributions of the main channel response parameters can be found in [14]. The correlation among the channels of the same indoor network is illustrated in Fig. 3 (a) and (b), and a detailed comparison based on the analysis of the Singular Value Decomposition (SVD) is carried out in [15].

A thorough validation of the overall simulator requires the comparison of simulated results with those obtained with actual modems. In principle, this must be done in a large number of indoor networks in order to verify the ability of the Channel Generator to produce statistically representative channels. However, since this capacity has already been thoroughly assessed, only one scenario might be considered. In this sense, it must be taken into account that while modems made by different manufacturers perform almost equally in high SNR scenarios, differences among them appear in bad channel conditions. This pitfall can be avoided by using a network with very lowly attenuated channels. It has been obtained by connecting up to six commercial HomePlug AV modems (Linksys PLE200) quite close to each other. In the simulator it has been replicated by manually configuring the Channel Generator. One of the modems acts a server, receiving the transmission from the clients. Each of them is connected through its Fast-Ethernet interface to a PC. The latter generates UDP traffic at a rate high enough to saturate the interface. Therefore, it can be assumed that the input rate to each modem is approximately 100 Mbps. The UDP throughput of the first client has been measured as the others were connected. This experiment has been repeated five times. The average values with their respective 95% confidence intervals, along with the simulated ones, are shown in Fig. 5. As seen, there is an excellent match between them.

4. Performance evaluation

In this section, the presented multicast algorithms will be evaluated. Firstly, the influence of the correlation among the channels of a given network on the throughput and on the delay is assessed. To this end, both the HPAV, as defined in the standard, and the modified version that includes the CGT algorithm will

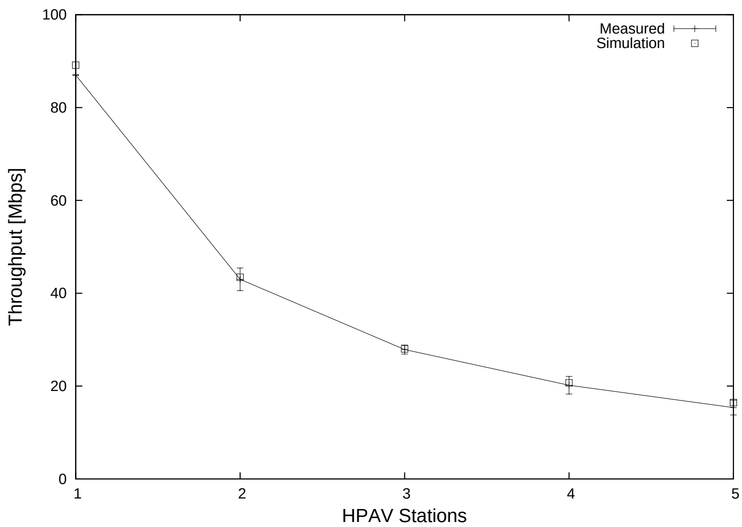


Figure 5: Simulator validation results

be used. Secondly, the performance achieved by the AMBM is compared to the one of the CGT. Finally, the performance of a video streaming service using the standard HPAV and the modified version with the GCT is assessed.

Unless otherwise stated, all the values has been obtained by averaging 50 indoor power line networks, which has proven to be sufficient to obtain statistically representative results. The following outputs from the simulator will be used:

- Throughput. Amount of useful data successfully received by the destination station in a given time period. Due to the MAC layer overhead, it will be always lower than the physical bitrate.
- Delay MAC. Time spent by the CSMA/CA protocol to successfully transmit a frame.
- Jitter. Variability over time of the MAC delay. It has been computed according to the definition given in RFC 3550 [20],

$$J(i) = J(i-1) + \frac{1}{16}\left(|D(i) - D(i-1)| - J(i-1)\right). \qquad (6)$$

- Latency. Time spent by a frame to cross the whole system, from its arrival to the transmitter station buffer to its fully reception at the destination.
- Frame Errors. Frame loss caused by a transmitter station buffer overflow (buffer size is limited to 1 MB).

4.1. Effect of the correlation among channels

This subsection analyzes the influence of the correlation among the channels of each in-home network on the performance. To this end, the HPAV, as defined in the standard, and with the CGT algorithm are compared in two scenarios. In one of them, the channels of each in-home network are uncorrelated, in the other, channels are generated using the generator proposed in section 3.1. Saturated conditions are assumed in all cases, i.e., each station has a new frame to be transmitted immediately after a frame transmission has been accomplished. Fig. 6 and Fig.7 depict the mean throughput and MAC delay experienced by the multicast clients as a function of the multicast group size. The 95% confidence intervals are also shown to assess the reliability of the results.

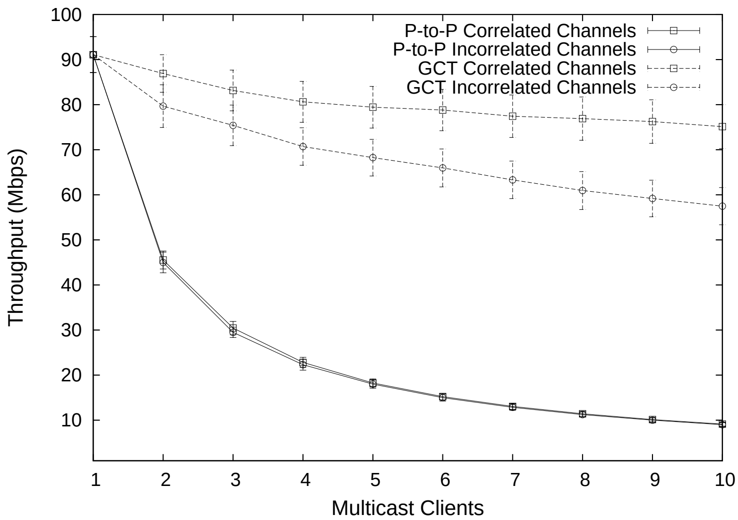


Figure 6: Throughput obtained with the HPAV, as in the standard, and with the GCT modification.

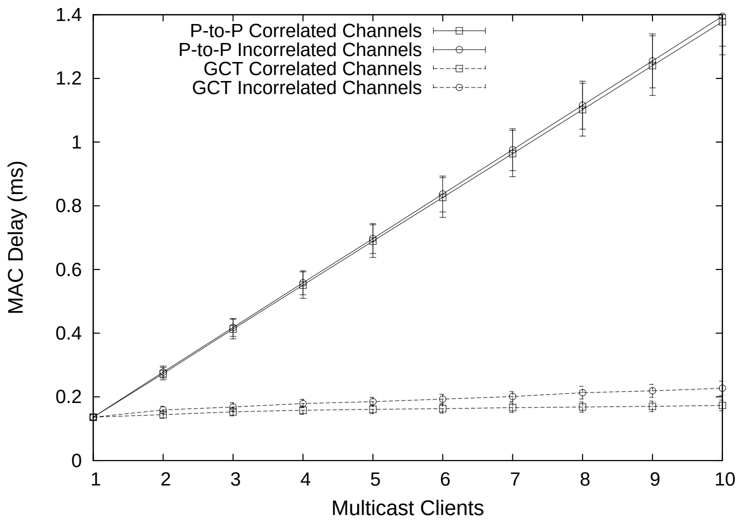


Figure 7: MAC delay obtained with the HPAV, as in the standard, and with the GCT modification.

Fig. 6 shows that, as expected, the correlation among channels has nearly no effect when the multicast is implemented as point-to-point transmissions. On the other hand, when the CGT is used, discarding this correlation leads to an underestimation of the performance, ranging from about 8% for two users to about 23% for ten users. Regarding the CGT algorithm, it is worth noting that it significantly outperforms the point-to-point solution for any number of multicast clients. Moreover, the improvement increases with the number of clients.

It should be mentioned that the GCT algorithm has been discarded as a multicast solution in other OFDM systems such as the 802.11 family standards. This conclusion has been traditionally extrapolated to PLC without taking into account the particularities of this environment. However, the presented throughput results show that it is a simple and effective solution for in-home PLC networks. Accordingly, all the channels used in the simulations of the subsequent sections have been obtained using the generator proposed in section 3.1.

Regarding the MAC delay, it can be seen that with the strategy used in the standard, it grows linearly with the number of clients. This is because between the transmission of two frames to a particular client, the transmissions to the rest of multicast clients should be made. On the contrary, this does not happen with the GCT algorithm, since all the transmissions are simultaneously received by all the group members. In this case, the delay increment is only caused by the decrease of the overall multicast capacity that occurs when the number of clients increases.

4.2. Performance of the AMBM algorithm

As mentioned, the AMBM algorithm is intended to increase the multicast performance in scenarios with a high number of users. Fig. 8 shows the multicast physical bit rate (C_M) obtained by the AMBM and the GCT for various multicast group sizes. Each curve has been obtained by averaging 200 power line networks. The AMBM algorithm provides better results than the GCT algorithm in all cases. As expected, the obtained gain increases with the number of multicast client.

To clearly assess the gain of the AMBM with respect to the GCT, the average bit rate gain of the former with respect to the latter is depicted in Fig.9. As seen, the gain increases with the number of multicast clients, leading to 10% for multicast groups with 10 members. The reason for this behavior is that the probability of having one user with bad channel conditions increases with the size of the multicast group. This limits the multicast bit rate attained by users with good channel conditions when the GCT algorithm is used, but has very little effect when the AMBM is used.

Up to now, only the physical bit rate has been explored. However, the AMBM requires the use of high layer coding to allow proper decoding of the information by users with different physical bit rates. As mentioned in section 2.3, around 4-5% of overhead is introduced when raptor codes are used. Hence, according to Fig.9, the AMBM will outperform the GCT only when the number of clients exceeds five, since the bit rate gain is higher than the coding overhead only from this point on. However, the introduction of a raptor encoder/decoder

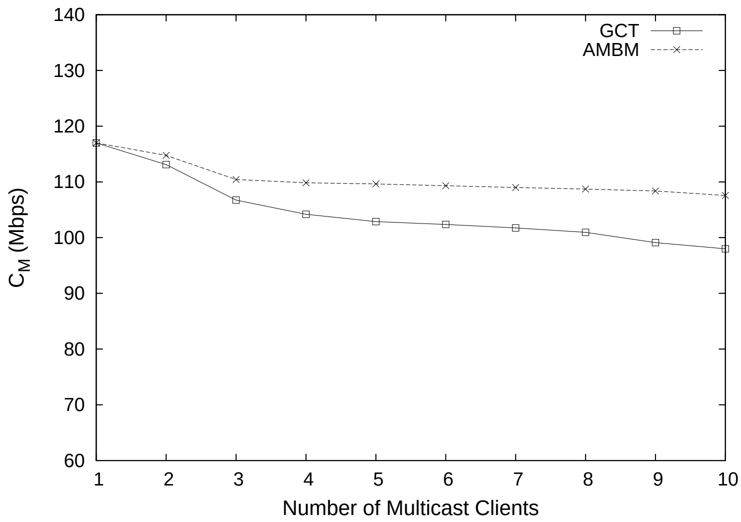


Figure 8: Multicast physical bit rate (C_M) obtained with the GCT and AMBM algorithms for different number of multicast clients

adds more complexity and resource consumption to the system, thus the use of AMBM algorithm is only recommended when an important gain is obtained. The extrapolation of Fig.9 for larger multicast group sizes indicates that significant gains can be obtained for groups with more than 15 clients, where gains larger than 10% will be obtained.

4.3. Video streaming evaluation

This section assesses the performance of the HPAV, as currently defined in the standard, and the modified version with the GCT algorithm when used to deliver MPEG-2 video. The QoS requirements for this service are summarized in table 3. Since this is not a real-time service it does not have any jitter or delay requirements.

Fig. 10 depicts the obtained throughput as a function of the multicast group size when the multicast video server is transmitting to the clients with and without sharing the channel with another station that is performing a data transmission (background traffic). Fig. 11 shows the latency and data loss in the same scenario.

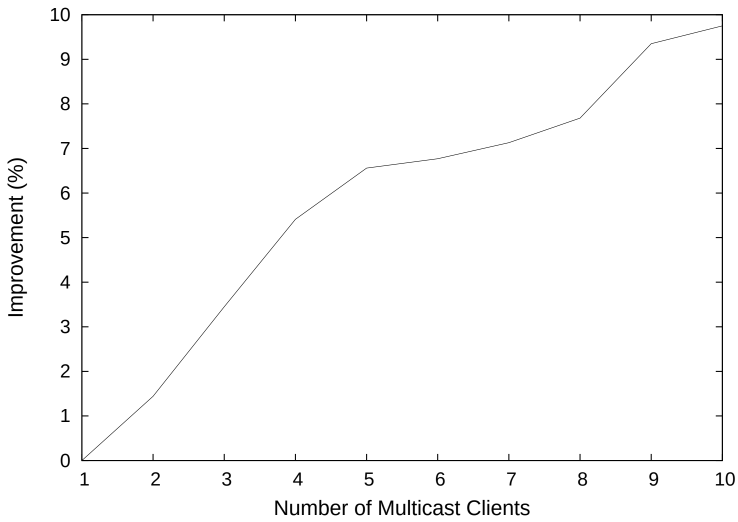


Figure 9: Average bit rate gain of the AMBM algorithm with respect to the GCT one

Table 3: QoS requirements for an MPEG-2 streaming service

Throughput	Packet loss	Latency
≈ 15 Mbps	5%	<4-5 seconds

It can be seen that the GCT algorithm offers much better performance than the HPAV standard for this multimedia service. When no other traffic is present in the network, the point-to-point solution currently implemented in the HPAV can be used to transmit multicast video to a maximum of four clients. At this point, the packet loss reaches 5.46%. From this value on, the throughput decreases and packet loss increases in such way that the service performance is severely degraded. When the channel is shared with a background data transmission, the concatenated point-to-point solution used in the standard leads to bad results even with only two multicast clients (9.46% of the packets are lost). On the other hand, the modified HPAV that includes the GCT algorithm achieves good performance in both cases (with and without background traffic) with up to ten multicast clients. In the figure, it can be seen that the results

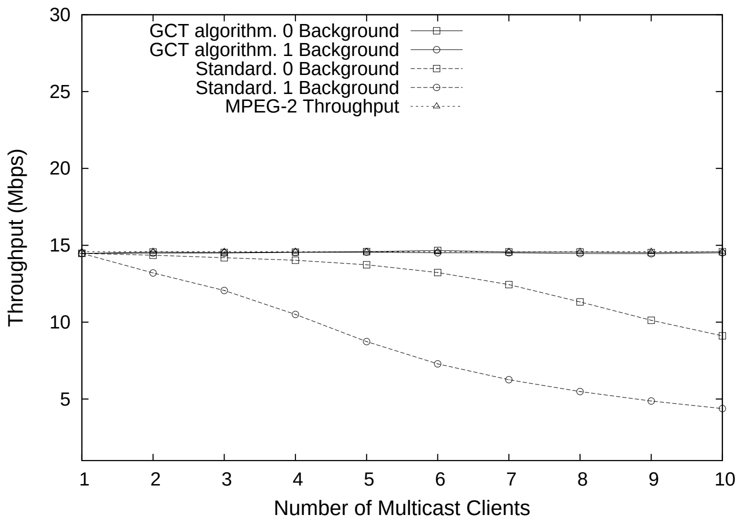


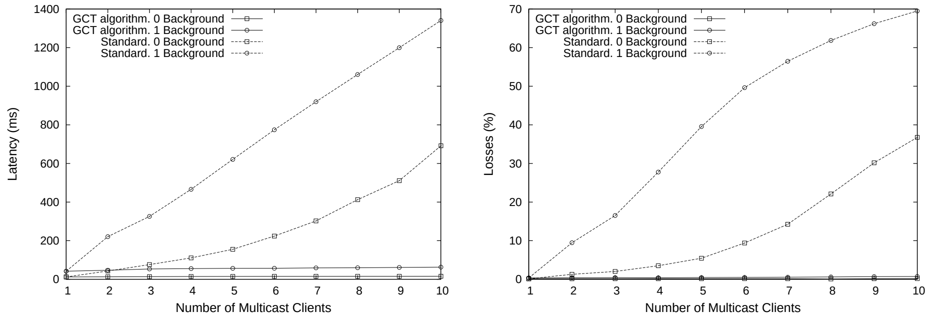
Figure 10: MPEG-2 throughput obtained with the HPAV, as in the standard, and with the GCT modification, with and without background traffic

offered by this algorithm perfectly fits with the traffic offered by the MPEG-2 encoder.

5. Conclusion

This paper has addressed the problem of multicast communications in HomePlug AV-based in-home networks. To this end, an in-home PLC simulator based on the HPAV standard has been presented. It implements the physical and MAC layers as well as traffic models for the most common home network services. A distinctive feature of this simulator is that the correlation among the channels established in a given home is similar to the one exhibited by actual channels. To the authors' best knowledge, this issue has been disregarded in previous multicast studies, leading to inaccurate performance estimations.

The proposed simulator is firstly used to assess the performance of standard HPAV multicast communications procedure. Since it translates the IP multicast transmissions to consecutive point-to-point transmissions, the attained bit rate decreases very rapidly as the number of users increases. Presented results



(a) Latency (b) Losses

Figure 11: MPEG-2 latency and packet loss obtained with the HPAV, as in the standard, and with the GCT modification, with and without background traffic

show that this poor performance can be notably increased with the quite simple strategy of using a common tone map for all the different multicast clients. This technique has been traditionally discarded because of the poor performance it achieves in wireless scenarios. However, the correlation among the power line channels established in a given network makes it useful for in-home PLC networks. For larger PLC networks, like hotels or offices, a new multicast strategy is proposed and evaluated. As an example, obtained results indicate that gains of up to 10% can be expected for multicast groups with 15 members.

Finally, the performance of a video streaming service delivered with the HPAV, as currently defined in the standard, and with the modified version that implements the common tone map is evaluated. It is shown that the latter is able to meet the QoS requirements with up to ten users, while the former might have difficulties even with two users.

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