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A Realistic HomePlug-AV Simulator for In-home Network Services Planning

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***Abstract*—In this work, a network simulator for power line communications based in the Homeplug-AV technology is presented. The simulator implements both the physical and the MAC layers, along with an in-home power line channel generator, which makes it very useful in a wide variety of network optimization procedures. To the authors' knowledge, performance evaluation of the MAC layer of Homeplug-AV by means of simulations has been always accomplished assuming excessively simplistic channel conditions. Therefore, this simulator represents an important contribution, as it includes a realistic physical model along with the CSMA/CA protocol described in the standard. In this paper, the proposed simulator is employed to evaluate the performance of the Homeplug-AV standard in an in-home network. The obtained results are then applied to video services planning in networks based in this standard.**

I. Introduction

Multimedia applications, such as High Definition TV, high-quality interactive games or audio/video conferencing, are becoming very important for the intelligent homes of the future. Therefore, it is necessary to implement a home network (also called in-home network) able to provide support for data transmission from a variety of sources.

Among the alternatives that could be used to set up an in-home network, PLC (Power-line Communications) has recently attracted much interest in the industry and the scientific communities. Power-line networks are easy to install and expand as they use the low-voltage wiring installed in the building. Therefore they provide a cost-effective solution for home communications. There are different PLC technology standards, but the most popular is HomePlug-AV (or simply HPAV) [1], which was presented by Homeplug Powerline Alliance [2] in 2005.

However, it is necessary to take into account that there are several aspects of the PLC medium that make it difficult to share resources fairly. The PLC channel is frequency selective and time variant, and exhibits a remarkable variation among locations, according to the network topology, the type of wires, and connected loads. Even in a specific in-home network, different characteristics can be found depending on the selected transmission path or the status of the electrical appliances.

The particular characteristics of the PLC channel make very difficult the development of a PLC network simulator. To the authors' knowledge, there are no simulators that implements both the physical and the MAC layers of the HPAV standard. In fact, the Homeplug-AV CSMA/CA evaluation literature usually employs very simplified physical layer models [3][4].

In this work, a PLC network simulator based in the HPAV technology is presented and used to evaluate the performance of an in-home network based in this standard. It implements both, the physical and the MAC layer. The former uses the channel model proposed in [5] and the OFDM system described in [6][7]. The MAC layer implementation is based in the CSMA/CA protocol detailed in [8]. Although, according to the standard, Homeplug-AV also provides a connection-oriented contention free service, based on Time Division Multiple Access (TDMA), it is not available in most commercial modems. Therefore, in this first version of the simulator only CSMA/CA contention service is implemented. However, as detailed below, the modular design of the simulator facilitates the later addition of the TDMA service.

The rest of the paper is structured as follows: section II describes the main characteristics of the simulator. Section III shows the simulation results for a typical in-home network. These results are used for network services planning in section IV. Finally, section V summarizes the main contributions of the work.

II. Simulator Description

A. Overview

The structure of the simulator is shown in Fig. 1. It consists of three blocks: the channel generator, the physical layer simulator and the MAC simulator. The former generates the channel responses and the noise for all the stations in the in-home network. At the transition instants specified in the input parameters, a long-term change in the network is simulated by connecting/disconnecting an electrical appliance. The physical layer simulator implements an OFDM system with the parameters of the Homeplug-AV standard. It computes the available bit-rate, $C_i(t)$, for each generated channel. These values are given to the MAC simulator, which simulates the Homeplug-AV CSMA/CA protocol with the number of stations and the traffic pattern defined in the input parameters. As a result, it provides the throughput, the frame delay and the jitter for each

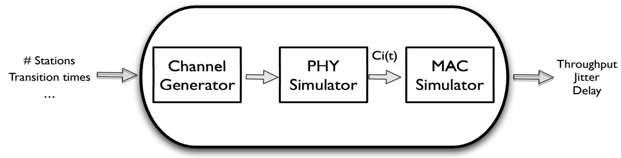

Fig. 1. Simulator structure overview

active station. It should be highlighted that the jitter has been calculated as defined in RFC 3550 [11],

$$J(i) = J(i-1) + \frac{1}{16}\left(|D(i) - D(i-1)| - J(i-1)\right), \quad (1)$$

where $D(i)$ represents the delay of the ith frame and $J(i)$ represents the jitter obtained after the reception of the ith frame. The reason is that most multimedia services specify their jitter requirements assuming that it has been computed as in (1).

B. Channel Generator description

In-home networks consist of a large number of cables interconnected in a tree-like manner and terminated in loads of diverse nature. The link between each pair of stations can be modeled by a main path from which a number of stubs or "bridged taps" are deployed. These stubs are ended in different load impedances. This work assumes that the lengths of the main path and of the stubs of different links are uncorrelated. The rationale is that stations are randomly distributed in the network and that the number of sockets is much larger than the number of stations. Moreover, it is assumed that each link can be modeled by a simplified topology with only seven line sections (the main path and three stubs) and a reduced set of loads impedance functions.

In these circumstances, the channel response of each link can be obtained by means of the channel generator proposed in [5]. Using its random generation mode, a different topology and loads configuration is generated for each link. Long-term changes are simulated by changing the impedance function connected to a randomly selected socket. The short-term variation of the channel is not considered. In this work, the lines length are generated according to a Gamma distribution with mean 27 and variance 486. This allows obtaining channels with a wider range of characteristics than the ones resulting with the uniform distribution used in [5].

The existing noise at each receiver socket is assumed to be composed of three terms: background noise, a couple of periodic asynchronous impulsive noise terms and a set of narrowband interferences. Three noise scenarios have been defined: heavily, medium and weakly disturbed. The power spectral density (PSD) of the background noise and the periodic asynchronous impulses have been taken from [9]. The pulse waveforms of the periodic asynchronous terms are repeated with a frequency of 26.3 kHz and 48.9 kHz, respectively. Both impulsive terms are assumed to be present all the time. The set of narrowband interferences is composed of 60 AM modulated signals and 2 narrowband FM ones. Each time a long-term channel occurs, the noise scenario at the receiver side is randomly selected.

C. PHY layer description

The physical layer simulates a pulse-shaped and windowed OFDM system as the one defined in the Homeplug-AV standard. The system parameters have been drawn from [6][7]. However, to speed up simulations, the channel coding block has been substituted by a constant coding gain of 12 dB. Nevertheless, the $16/21$ code rate is taken into account. The number of bits per carrier is computed using the expression given in [10], which implicitly assumes that both the noise and distortion are Gaussian. To compensate for the two aforementioned approximations, a 3 dB system margin has been included. The bit error rate (BER) is fixed to 10^{-5}.

D. MAC layer description

The CSMA/CA protocol employed in the HomePlug-AV standard is the same to the one in the HomePlug 1.0. For the sake of completeness, this section highlight the main features of the detailed description that can be found in [8]. The protocol uses priority resolution and random backoff in order to resolve collisions efficiently and to provide QoS. Each transmission is predeced by two priority resolution slots called PRS0 and PRS1. There are also two gaps, one after a successful transmission and another before the reception of the response, called CIFS and RIFS respectively. The protocol defines four priority levels, named CA3 (the highest) to CA0 (the lowest). All stations having frames for transmission are required to send signals in the priority resolution slots designated for their priority level. Stations with CA0 send no signal in both PRS0 and PRS1, and those with CA1 send signals only in PRS1. Stations with CA3 or CA2 send signals in PRS0, but only stations with CA3 send signals in PRS1. The signals in the priority resolution slots can be sensed on the medium and they cause the low priority stations to defer.

Table I shows the values employed in this work for these parameters and Fig. 2 shows 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), that cannot be longer than 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 positively 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.

III. Simulation Results

In this section, simulation results are presented and discussed. Firstly, the statistical distribution of the throughput

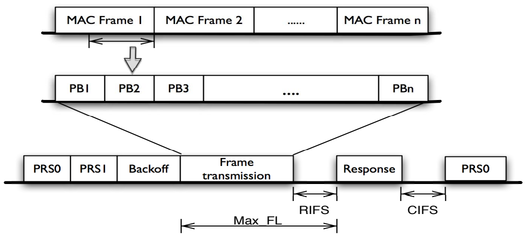

Fig. 2. Timing sequence for the transmission of MAC frames

TABLE I
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

when only one station is active in the network is obtained, i.e. there are two stations but one always acts as the transmitter and the other as the receiver. This may model the connection between the multimedia player and the in-home server or the connection between a PC and a printer. Then, the evolution of the throughput, the delay and the jitter as the number of active stations increases is also presented.

A. *One active station scenario*

The objective of this section is to determine the statistical distribution of the throughput that can be achieved in an in-home network when only one station is active. To this end, 100 in-home links have been considered. This constitutes an statistically representative set of channels. Home appliances connections/disconnections are not considered and the total simulation time in each case was 300 s. The cumulative distribution function (CDF) of the throughput values is depicted in Fig. 3. As seen, the median value of the throughput is 80.96 Mbps (the mean throughput is 73.77 Mbps). The highest throuhgput is 102.3 Mbps, which corresponds to 133 Mbps of physical bit-rate, while the smallest is 8.31 Mbps, which corresponds to 10.8 Mbps of physical bit-rate. All these values are consistent with those that have been observed in a real in-home Homeplug-AV network.

B. *Multiple active stations scenario*

In this section, the evolution of the throughput, the delay and the jitter as the number of active stations increases is obtained. Results have been computed by averaging over 50 in-home networks simulated over 5000 seconds. In order to simulate the real behavior of an in-home network, 25 equally spaced long-term changes have been provoked in each network. This leads to 200 seconds between changes, which is much higher than the time taken by the physical and MAC layers to stabilize.

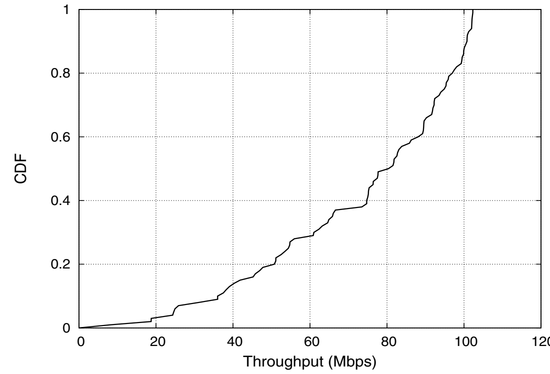

Fig. 3. One station throughput CDF

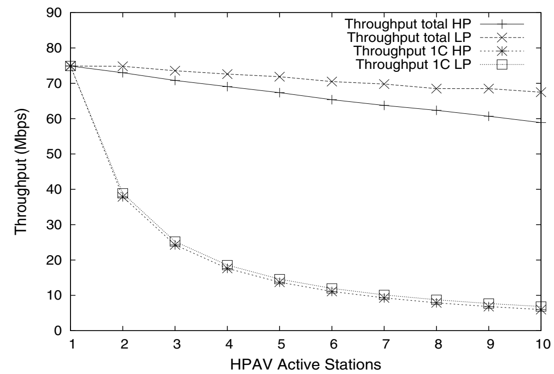

Fig. 4. Total network throughput and one client throughput versus the number HPAV active stations

In this circumstances, it has been verified that 25 long-term changes are high enough to obtain statistically representative results, i.e. all the stations obtain approximately the same average performance.

In these simulations the frame arrival rate is high enough to assume saturation conditions, i.e all the station have frames to transmit in every access to the channel. Fig. 4 shows the throughput for a single station and the total network throughput vs the number of active stations. Two cases are displayed, one in which all the stations have the highest priority (HP) and other in which all the stations have the lowest priority (LP). It can be observed that the stations priority has a relatively important impact in the throughput, about 12% of throughput loss for 10 active stations. This behavior is in accordance with the results shown in [8]. Similarly, it can be observed that the throughput achieved by each active station is almost inversely proportional to the total number of active stations. This result indicates that the protocol is well designed, as the throughput loss caused by the contention is approximately independent of the number of active stations.

To evaluate the impact of the collisions in the total network throughput, it is also interesting to represent the normalized throughput as the number of active stations increases, and the number of collisions per second that each station suffers. These results are shown in Fig. 5 and Fig. 6 respectively. From these

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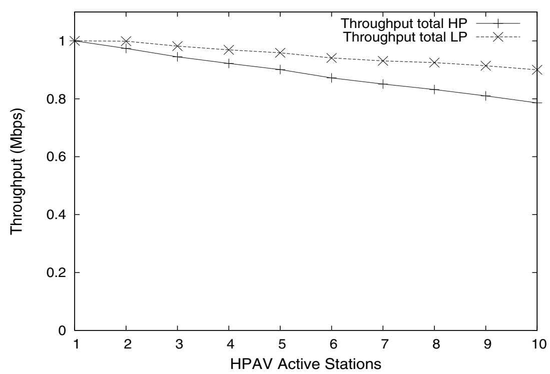

Fig. 5. Normalized total network throughput versus the number HPAV active stations

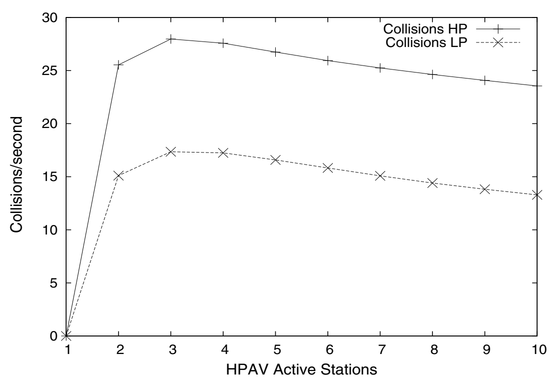

Fig. 6. Number of collisions per second for each station versus the number HPAV active stations

results it can be seen that, for ten active stations, the collisions produce a 22% throughput reduction for the high priority case and a 10% for the low priority one. The representation of the collisions per second for each client shows a maximum when there are three active stations in the network. From that value on, although the total network collisions increase, the number of collisions per active station decreases. The reason of this decreasing behaviour is that the backoff procedure uniformly distributes the channel accesses among the contending stations. Therefore, as the number of active stations increases, the number of channel accesses per station decreases, causing a reduction in the number of collisions that each station suffers.

Finally, the average frame delay and jitter are also represented in Fig. 7 and Fig. 8 respectively. As before, the delay and the jitter values are affected by the stations priority. It is important to note that the standard defines a larger backoff procedure contention window for the low priority group (CA1 and CA0) in order to support the different delay characteristics of the different priorities [8]. Therefore, the low priority group suffers less collisions and it obtains a larger MAC throughput and lower MAC delay and jitter as seen in the presented results.

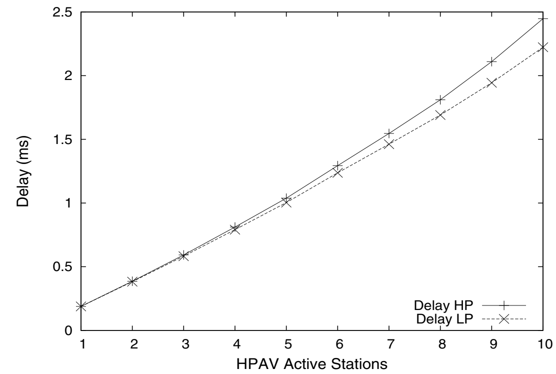

Fig. 7. Average MAC frame delay versus the number HPAV active stations

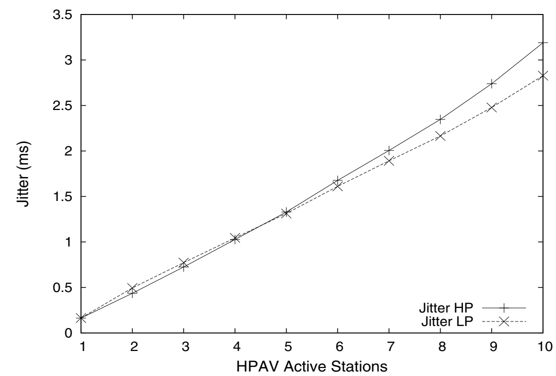

Fig. 8. Average MAC frame jitter versus the number HPAV active stations

IV. Network services planning

In this section, the proposed simulator is applied to network services planning. Concretely, the video transmission case is considered. Active stations want to start a video session. The QoS requiered by high definition TV (HDTV) and standard definition (STDV) services are shown in Table II [12]. It can be seen that, while the delay requirements are the same for both cases, the bandwidth values are rather different.

In order to evaluate the maximum delay condition, the CDF of MAC frames delay vs the number of active stations is shown in Fig. 9. It is worth noting that the x-axis is in logarithmic scale. As seen, there are two main frame types according to their delay. The first type of frames are the ones that are sent back to back in the same burst or channel access. Hence, their delay is basically equal to the transmission delay. In Fig. 9, these frames are represented in the first part of the CDF curve, which has a nearly infinite slope. As observed, these frames are approximately 85% of the total number of frames. Their delay vary between 0.09 ms, which is the transmission time employed by the fastest station (132 Mbps physical bit-rate) to transmit a 1,500 bytes frame, to 1.01 ms, which is the transmission time employed by the slowest station (12.1 Mbps physical bit-rate). The second type of frames are those that require more than one channel access for their transmission. As shown in Fig. 9, their delay is mainly determined by the backoff procedure. Therefore, it is strongly dependent on the

TABLE II
VIDEO TRANSMISSION QOS PARAMETERS.

Application	Offered Load	Maximum delay	Frame size
HDTV	19.2-24 Mbps	200 ms	1500 bytes
SDTV	4-5 Mbps	200 ms	1500 bytes

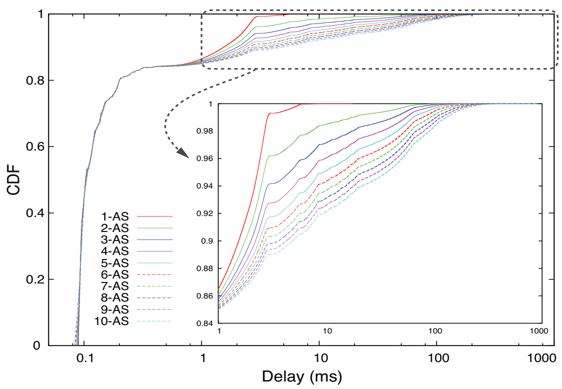

Fig. 9. MAC delay CDF versus the number of HPAV active stations (AS)

number of active stations. This kind of frames represent the remaining 15% of the total frames.

Fig. 9 can be used to determine the probability that a frame exceeds the maximum delay requirement in Table II. Results are shown in table III. Assuming that in higher layers the frames that exceed the maximum delay restriction will be discarded, these delay exceeding probabilities can be considered as losses. According to [13] the maximum packet loss ratio (PLR) for a good quality video reception is 0.01. Therefore, if only this condition is considered, all the video transmissions can be accomplished without problems.

Another important consideration is the number of stations that cannot succesfully carry out the video transmission due to bandwidth limitation. As it can be seen in figure 4, for HDTV transmissions the maximum number of simultaneous transmission is three, while for SDTV up to ten video transmission can be succesfully done. This is the most restrictive condition, so it limits the number of video transmission of each type that can be simultaneously performed in a Homeplug-AV network.

V. CONCLUSION

In this paper, a simulator of in-home Homeplug-AV networks has been presented. It includes a realistic channel generator along with the physical and the MAC layers defined in the standard. Hence, performance of the MAC layer can be accomplished over realistic channel conditions. This represents an important contribution because, to the authors' knowledge, performance evaluation of the MAC layer of Homeplug-AV by means of simulations has been always accomplished assuming excessively simplistic channel conditions.

The proposed simulator has been employed to evaluate the performance of in-home networks as a function of the number of active stations. The individual and the overall network throughput, the delay, the jitter and the number of collisions per seconds have been obtained. The influence of the stations priority has been also studied.

As an example, obtained results have been employed to evaluate the viability of transmitting high definition and standard definition TV over the in-home network. However, the simulator can be applied to a wide variety of Homeplug-AV network optimization procedures, e.g. cross-layer protocol design or de-jitter buffers design.

TABLE III
PROBABILITY OF EXCEEDING MAXIMUM FRAME DELAY REQUIREMENTS FOR DIFFERENT NUMBER OF ACTIVE STATIONS

# stations	Probability	# stations	Probability
1	0	6	$3.9 \cdot 10^{-4}$
2	$5.4 \cdot 10^{-7}$	7	$7.9 \cdot 10^{-4}$
3	$7.38 \cdot 10^{-6}$	8	$1.34 \cdot 10^{-3}$
4	$4.24 \cdot 10^{-5}$	9	$2.1 \cdot 10^{-3}$
5	$1.56 \cdot 10^{-4}$	10	$2.93 \cdot 10^{-3}$

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