Power Line Communication standards for in-vehicle networks

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***Abstract*—This paper deals with the in-vehicle networks. We propose to study a network which do not need new wires called Power Line Communication (PLC). Indeed, the automotive communication networks has evolved and the electronic devices in-vehicle are widespread. For example, drive-by-wire systems have actuators, engine, sensor and microprocessor to replace mechanical or hydraulic systems in vehicles. Moreover, electronic control unit (ECU) communicates and exchanges data. These needs of data sharing between ECU or between new services like multimedia involve to research new buses of communication with high throughputs. The CAN, LIN and FlexRay are wire protocols of communication usually used in the same vehicles and FlexRay has the highest throughput (10 Mbps). It appears that with the increase of electronic devices there is a wire harness bottleneck. To reduce wires and to have high throughputs (>10 Mbps), we propose to study the feasibility of PLC indoor standards in-vehicles. PLC are usually used in indoor networks. In this paper, a comparison of two PLC standards with throughput measurements thanks to commercial PLC modem in-vehicle is carried out: HomePlug Av (HPAV) and High Definition Power Line Communication (HD-PLC).**

I. Introduction

The automotive industry use more and more electronic devices for the security, to replace the mechanic systems (X-by-Wire), for multimedia. A growth of wire harnesses appears and a need of high throughput involve to find new buses of communication. Up to now the CAN, LIN and FlexRay are buses of communication usually used in-vehicles. And FlexRay has the highest throughput (10 Mbps).

We propose to study network which do not need new wires called Power Line Communication (PLC). Indeed PLC is an interesting solution for indoor networks and now the PLC are commonly used. That's why, several standards appeared on the market like HPAV, HD-PLC Alliance, Spidcom or Universal Powerline Alliance (UPA). We study two different indoor PLC modems using HomePlug Av [1] and HD-PLC [2] standards in order to have an idea about the feasibility to adapt these standards in a car for example. More particularly, we are interested by the behaviour of PHY/MAC parameters of these standards to evaluate the feasibility of high throughput over DC line in-vehicle. In this paper a comparison between the two standards is done in term of throughput. In fact, we studied the TCP throughput between two PC in different points of a car. We used different typical scenario like car moving in order to test several use cases.

TABLE I
MAC/PHY parameters: HPAV vs HD-PLC; NC = Not Communicated.

Parameters	HPAV	HD-PLC
Scrambler	yes	NC
FEC	Turbo code	LDPC; Convolutional, Reed Solomon code
Interleaver	yes	NC
Mapper	QAM 2-1024	PAM 2-32
Modulation	Windowed-OFDM	Wavelet-OFDM
IFFT/FFT size	3072	-
Number of carriers	1536	512 (extendable to 2048)
Sampling frequency	75 MHz	62.5 MHz
Bandwidth	2-28 MHz	2-28 MHz
Inter-carrier space	24.414 KHz	122.07 KHz
Symbol duration	40.96 μs	8.192 μs
Guard Interval duration	5.56 μs or 7.56 μs or 47.12 μs	-
MAC layer protocol	Hybrid: CSMA/CA & TDMA	Hybrid: CSMA/CA & TDMA

II. PLC in-vehicles

To our knowledge there is no PLC device in-vehicle with high throughput, i.e. throughput higher than FlexRay (10 Mbps). We can however mention a device of Yamar [3] company which proposed a solution based on transmission over DC lines and CAN protocol. But, the maximum throughput of the Yamar device, namely DCB500, is only 500 Kbps. In [4], a PLC communication in-vehicle has been demonstrated. This PLC communication was based on single carrier spread spectrum technology and it achieved a throughput of only 50 Kbps. In [5], [6] a PLC communication based on a multicarrier modulation has been demonstrated and unlike the two previous applications, multicarrier modulation achieved higher throughputs.

III. Comparison of MAC/PHY layer of HPAV and HD-PLC

We study MAC/PHY parameters of HPAV and HD-PLC standards. Tab I shows the interest of MAC/PHY parameters of standards HPAV and HD-PLC. Both use OFDM (Orthogonal Frequency Division Multiplex) multicarrier modulation but they do not use the same window shaping.

The HomePlug AV standard is the second generation of PLC systems developed by the HomePlug Powerline Alliance. Now it is suitable for multimedia applications like HDTV or VOIP. The PHY layer uses a Windowed-OFDM modulation. The HPAV can use different modulation order from BPSK (Binary phase-shift keying) up to 1024 QAM (Quadrature Amplitude Modulation) for each sub-carriers according to the channel characteristics. To counteract the channel multipath effects and so the intersymbol interferences, the HPAV uses a guard interval (GI). Moreover, several GI (5.56 μs, 7.56 μs or 47.12 μs) can be used depending on the channel and so the throughput can be improved. A frequency mask is used to avoid interferences mainly with amateur radio bands. This is the reason why the pulse-shaped OFDM symbols is different than the classic rectangular window. Thanks to this specific window, the out-of-band noise is reduced and the nocthes are deeper. The MAC layer is based on a hybrid acces mechanism: Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) and Time Division Multiple Access (TDMA). A Central Coordinator (CCo) controls the PLC network. A channel sounding is carried out by the receiver which communicates the result to the CCO. Then, the CCO uses this channel estimation in order to establish a specific QAM modulation for each OFDM sub-carrier. HPAV uses a two-level MAC framing scheme. Indeed, the MAC frames are divided into 512 bytes segments called PHY Block (PB). An uncorrectable Forward Error Correction (FEC) code is used and a header is added with the numbers of the PB. Therefore, with this strategy, it is possible to retransmit only the damaged PB detected.

The HD-PLC alliance [2] (HD-PLC) is an additional group which promotes the PLC networks based on its HD-PLC technology. It is based on a specific OFDM modulation called Wavelet-OFDM which exploits the Wavelet transform. It appears with this modulation that the notches are deeper than OFDM realized with IFFT/FFT. Moreover, Wavelet-OFDM does not use guard interval and so it has a better spectral efficiency than OFDM modulation with guard interval. In contrast to HPAV, in the HD-PLC protocol, the baseband data are modulated by a Pulse-Amplitude Modulation (PAM) with an order from 2 to 32. The MAC layer uses an hybrid TDMA and CSMA/CA protocol synchronized thanks to the AC line cycle.

IV. Throughput measurement: testbed

The study of PLC throughputs is realized with PLC modems used in indoor networks. Indeed, these modems are commonly used in indoor networks and high throughputs have been demonstrated. It seems to be interesting to used their in-vehicles. The power line network in-vehicle is however different of those in a house. That's why, the modems have been modified to be used and plug into a car. The only modifications affect the coupling and the power supply. For HPAV, we used a Devolo 200Av modem [7]. For HD-PLC, we used a PLC Panasonic BL-PA510KT modem [8].

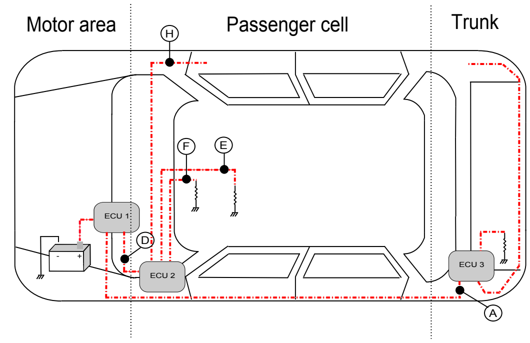

Fig. 1. Measurement scheme: the different uppercases represent the measurement points.

Fig. 1 illustrates the wiring harnesses of the Peugeot 407 SW car that was used. It represents the electrical supply network, the different positions (A, H, ...) of our PLC measurement points and the ECUs that controls the electronic systems in the vehicle. We considered several use cases that can happen in-vehicles. Accordingly, four typical scenarios for measurements have been studied:

1) Car with engine turned off.
2) Car with engine-turned but not moving.
3) Car with engine-turned but not moving and effects of lightning, warnings, radio, windscreen wiper, electric windows.
4) The car in motion and the effects of the equipments like in 3).

For our measurements, we use a test bed with two PLC modems and two computers (PC) which are plug into the different points shown Fig. 1. For example, if we want to study the TCP throughput measurement between A and D that we call path AD, we used a PC in A with a PLC modem and the same configuration in D.

The throughputs are measured associated with the payload ignoring headers. The throughput is also called Goodput according the definition in section 3.17 in [9].

V. Results and discussion

A. Results

Fig. 2, we show a comparison between the power spectrum of HD-PLC and HPAV. A spectrum analyzer is used in point A during a PLC communication between point A and D. We used a resolution bandwidth (RBW) of 10 kHz and the MAX Hold function. The power spectral density specified in HD-PLC and HPAV standards is defined with a maximum power spectral density (PSD) of -50 dBm/Hz. Fig. 2 we show the power (in dBm) versus the frequency. Like $P_u = PSD + 10 \times log_{10}(RBW = 10kHz)$ we can verified that the power spectral mask is compliant with PLC indoor specifications. Lastly, we can verified that HD-PLC has notches deeper than HPAV.

Fig. 3 and Fig. 4, we show insertion gain $|S_{21}|(dB)$ for different paths and three use cases. Fig. 3 shows paths between the rear area and the front area. Fig. 4 shows paths in the

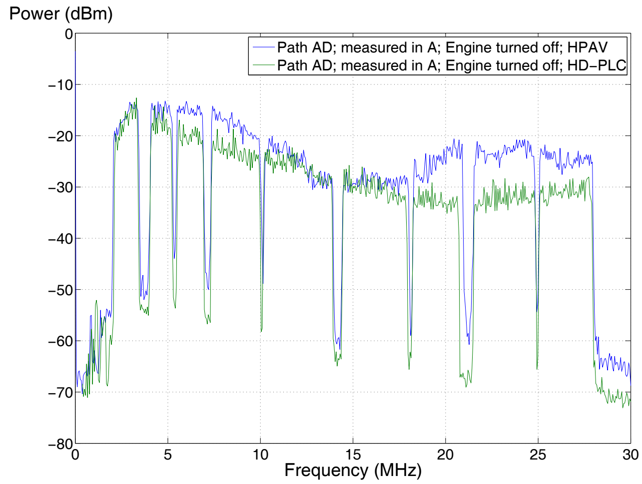

Fig. 2. Power spectrum of HDPLC versus HPAV ; Path AD; measured in A; scenario 1); Spectrum analyzer: Max Hold, RBW=10 kHz.

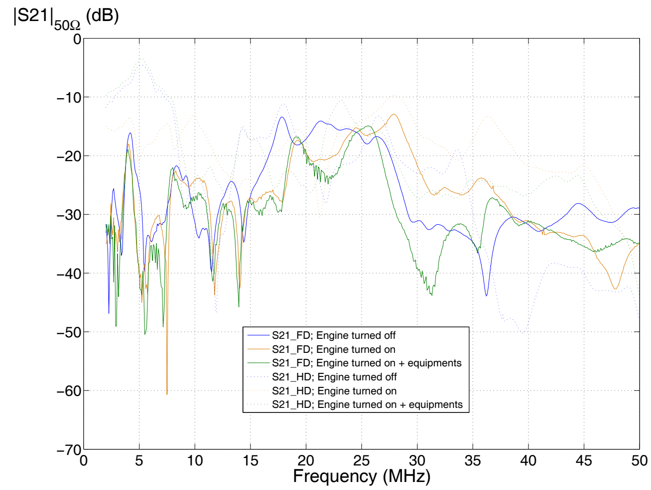

Fig. 4. Insertion gain ; Path FD and HD which are paths in front area; Engine OFF, engine-turned and engine-turned + equipments.

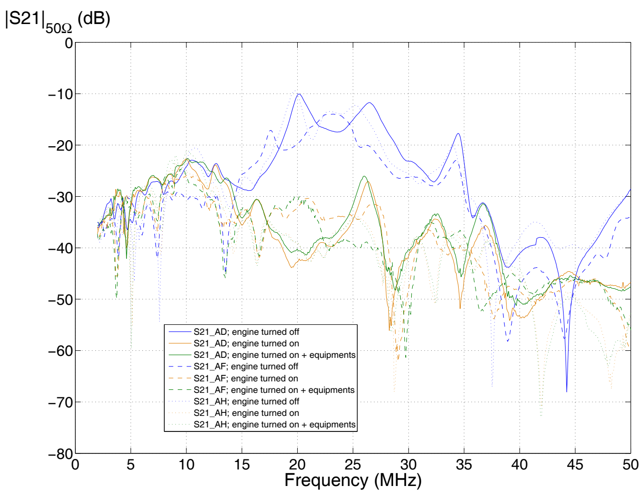

Fig. 3. Insertion gain ; Path AD, AF and AH which are paths between rear and front area; Engine OFF, engine-turned and engine-turned + equipments.

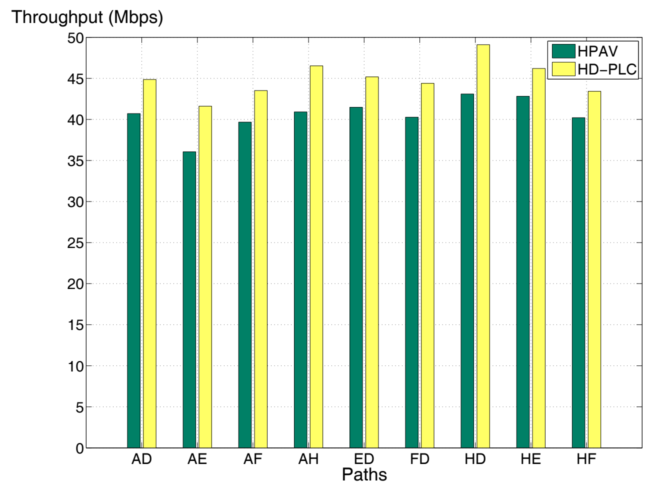

Fig. 5. Throughputs for different paths in-vehicle with scenario 1): comparison between HPAV and HD-PLC.

front area. We can see that from 17 MHz to 30 MHz the insertion gain of the paths AD, AF and AH, when the engine is turned off, are higher than the other cases. Therefore, we notice a difference when the engine is turning. Fig. 4, differences between use cases is less important. Moreover, the insertion gain are 10 dB higher for the paths in front area than Fig. 3.

Fig. 5 shows different throughputs for different paths in-vehicle with scenario 1). Throughputs with HD-PLC modems are higher than HPAV for each paths in-vehicle with this scenario. Throughputs are higher than 40 Mbps and so higher than FlexRay protocol (10 Mbps) which is usually used in-vehicle. We observed also that all paths have the same throughput for each of PLC standards.

Fig. 6 and Fig. 7 show different throughputs for different paths in-vehicle and for three scenarios respectively for the HD-PLC and HPAV standards. Like for the scenario 1) throughputs are higher than FlexRay protocol (10 Mbps) but the throughputs are about 20 Mbps. However, we remark that HPAV throughputs are higher than HD-PLC. In fact, for all the paths, throughputs are about 20 Mbps for HD-PLC and 25 Mbps for HPAV. The path HD is however different than others with higher throughputs for the two standards. Moreover, for this path there is no differences between the scenarios. The measurements show also that the throughputs are not modified by the scenarios 2), 3) and 4).

Fig. 8 and Fig. 9, we consider an other analysis which use a spectrogram. The spectrogram is a representation of the spectrum over time. We recorded power spectrum during 150s and we displayed each recording versus frequency. With a spectrogram we can have a time frequency view of the channel and the transmission between two points. The same file size is sent from A to D with HPAV or with HD-PLC modems and with different scenarios during 150s. We remark a throughput

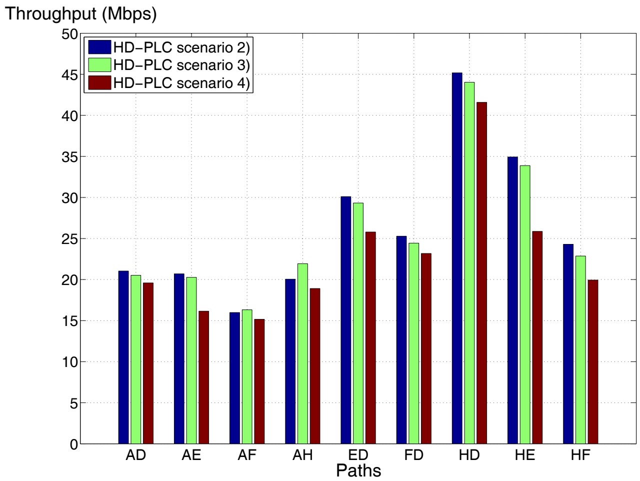

Fig. 6. HD-PLC throughputs for different paths in-vehicle for scenario 2), 3) and 4).

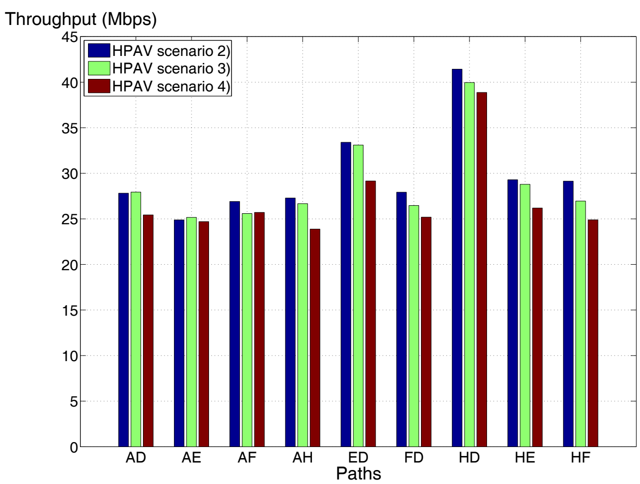

Fig. 7. HPAV throughputs for different paths in-vehicle for scenario 2), 3) and 4).

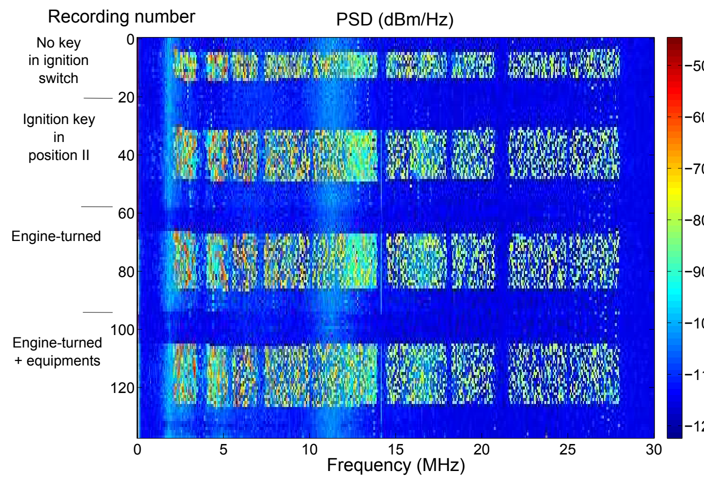

Fig. 8. Spectrogram measured in D; HDPLC communication for the path AD and for several scenarios.

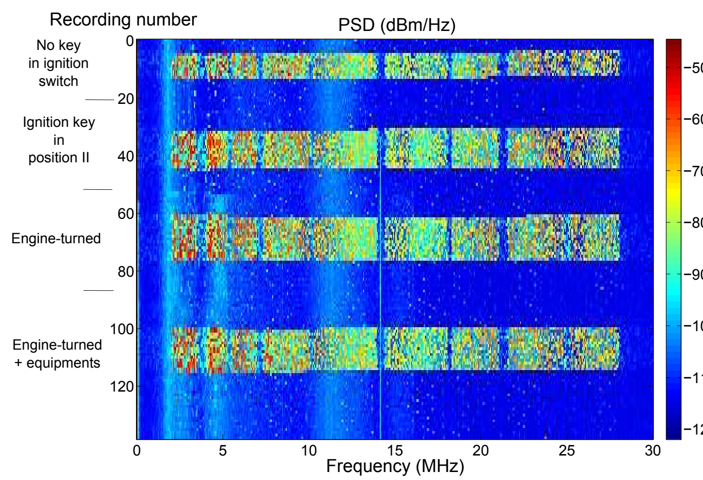

Fig. 9. Spectrogram measured in D; HPAV communication for the path AD and for several scenarios.

fall when the ignition key is turned in position II like it is specified in [10].

Fig. 10, we show the PSD for an HPAV and HD-PLC communication between the point A and D. We show also in the same figure the maximum ambient noise. This result has been compute like the maximum at each frequency of a recording of several noise spectrum measurements during $140s$.

Fig. 11, we show the maximum PSD ambient noise in point D for several scenarios. Each curves have been compute like in Fig. 10. We can see that the ambient noise is high in the band [2-7] MHz and [9-12] MHz and from 17 MHz up to 30 MHz the ambient noise is flat at about -110 dBm.

B. Discussion

In our measurements setup, the PSD of commercial modem is about -50 dBm/Hz (Fig. 10). With the injected power by the modified commercial modem on the DC line, the communication is not dependent of the topology. Indeed, all the paths have the same throughput whatever the scenario except for the path HD. In [6], authors explain that the communication is dependent of the topology when the power injected is low. Indeed, according to they, with a PSD mask of -60 dBm/Hz, there is no differences between paths called direct and indirect. And with a PSD of -80 dBm/Hz the throughputs are dependent of the topology.

We observe however that throughput are not the same if we take into account the scenarios. When we compare the throughput versus the scenario, we see a difference between the scenario 1) and 2), 3), and 4). Moreover, the same throughput fall is observed for HD-PLC and HPAV standards. According to us, this difference can be explained by the channel gain. Indeed, Fig. 3 and Fig. 4, we can see that the channel gain is lower except for the path HD with the scenario 2), 3) and 4). In [10] a similar phenomenon has been

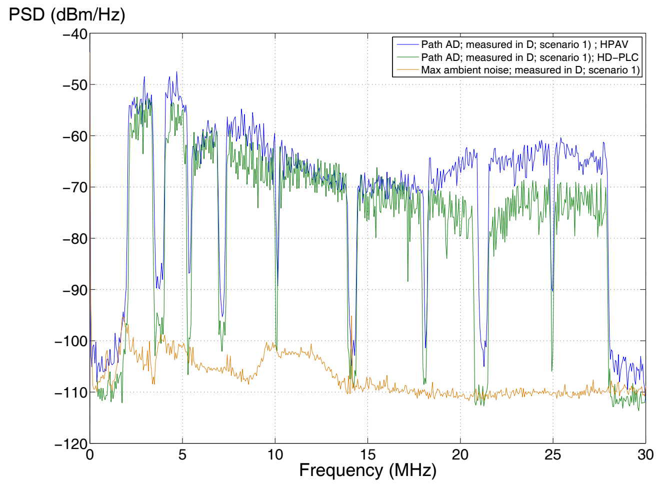

Fig. 10. PSD HPAV and HD-PLC in point D for a PLC communication between A and D; maximum ambient noise in point D.

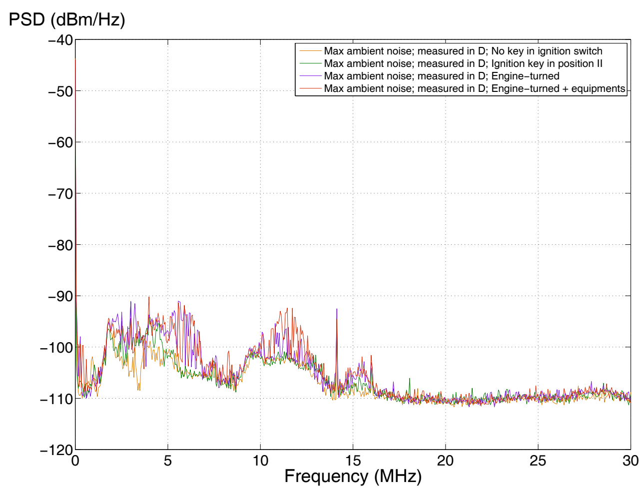

Fig. 11. Maximum ambient noise in point D.

observed and his impact of the channel gain. The differences of throughputs between scenarios are also show thanks to the spectrograms Fig. 8 and Fig. 9. These measurements show the throughput fall when the ignition key is in position II. Moreover, the ambient noise on the DC line increase when the key is in position II. When the ignition key is in position II, the insertion gain is lower and the noise level is higher, therefore the bit-loading algorithms of HD-PLC and HPAV provide an adaptively modulate different sub-carriers according to the new signal-to-noise ratio (SNR). That's why, we have a throughput fall of about half in order to have a robustness communication.

Finally, if we compare these results with an other PLC communication standard (Spidcom) studied in a previous study [11], we notice that HD-PLC and HPAV throughputs are better. For example, for the AD path, we have only a maximum throughput of 16.5 Mbps for Spidcom.

VI. Conclusion

We have setup an in-vehicle PLC communication system using existing wires based on commercial solution. Throughputs higher than FlexRay have been achieved. The HD-PLC and HPAV standards have similar performances over the DC line in-vehicle. Indoor PLC standards HD-PLC and HPAV are very similar and the greatest number of the PHY parameters can be used in-vehicles. However, some algorithms to enhance the efficiency can not be used in-vehicles like the 50 Hz synchronization or like channel adaptation based on cyclo-stationnary noise of indoor PLC. Moreover, specific PHY parameters optimisation can be achieved to improve the PHY rate thanks to in-vehicle channel measurements and characterization. Moreover in term of complexity Wavelet OFDM and Windowed OFDM are also similar [12]. Finally, the PLC network in-vehicle seems to be an efficient solution for high throughput applications like multimedia or rear camera [13].

Acknowledgment

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