Theoretical maximum data rate estimations for PLC in automotive power distribution systems

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***Abstract*—This paper discusses the limitations of power line communication (PLC) in vehicles, regarding system loads, transceiver coupling circuits and cable topology. Firstly, ECU input impedances were analyzed to obtain typical termination load conditions in modern vehicle power supply systems. Coupling circuits and cable harness topologies for the power distribution network were proposed, as well. Then, the common applied structure (tree topology) from modern vehicles was analyzed. EMC is considered by analyzing immunity and emission in vehicle. Three exemplary topologies of in-vehicle power supply system were analyzed. It has shown that ECU number and number of star points have significant influence to data transmission in PCL. Also, worst and best conditions for data transmission has been found based on retrieved channel characteristics and signal to noise ratio (SNR) approximations considering that the noise limit level in automotive power supply system equals to CISPR25 conducted emission limits.**

***Keywords*—In-vehicle power line communication (PLC), EMC, SNR, Immunity, Emission**

I. INTRODUCTION

The demand for more functions in automobiles leads to a higher number of electronic control units (ECUs), actuators, and sensors. As a consequence the wiring system becomes more complex, heavy and voluminous. Power line communication (PLC) can be an alternative or extension to the existing bus systems in nowadays vehicle (LIN, CAN, FlexRay, MOST and recently Ethernet). PLC might be able to compete with the abovementioned bus systems in terms of data rate and reliability, when some constraints are met in the power supply system. These constrains need to be defined and have to be considered by car manufacturers when designing the onboard systems.

Several publications discussed the integration of PLC in onboard power distribution networks, e.g. [1] for channel characterization and [2] for impulsive noise characterization in vehicles. A state-of-art research overview on PLC for transportation systems can be found in [4]. They summarize channel-modelling approaches for harness topologies to perform a statistical analysis of the channel properties. From analysis of transmission line models and measurement-based multipath-models it turns out, that such multibrunch wiring structures have a frequency-selective fading channel and transfer function, which depends on operating condition of the vehicle. Probability density functions or cumulative distributions of some representative parameters, such the mean attenuation or the coherence bandwidth, are referenced. Investigations are often based on out-of-date power distribution structures, where power loads are switched directly or via relays. Such structures lead to a time variant channel characteristic, which may affect reliability of communication. In many modern passenger vehicles, load states are controlled solely by ECUs that are connected by a tree-like topology to the power supply - battery and alternator. In this work, modern vehicle load conditions, topologies and channel characteristics were analyzed, in order to find appropriate solutions for PLC. Signal integrity, electromagnetic emissions and immunity were discussed. It is assumed that the frequency range below 30 MHz is appropriate for vehicle PLC according to many consumer electronics PLC solutions [8].

II. INPUT IMPEDANCE OF TYPICAL VEHICLE ECUS

Digital electronics (e.g. µC) in an ECU require a stable voltage of 5 V, 3.3 V or less. Fluctuations of µC supply voltage can lead to malfunctions. To provide a stable voltage a voltage regulator, combined with a stabilizing and protection network is typically applied in ECUs. Fig. 1 shows a typical circuit of a 12 V supply ECU input.

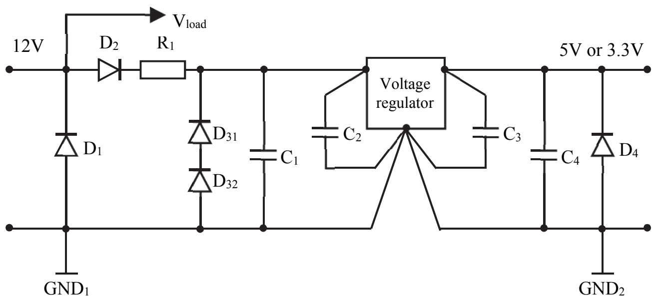

Fig. 1. Typical power supply circuit for vehicle ECU with stabilizing and protection network [4].

As shown in the circuit several capacitors and diodes are necessary. Generally, capacitors C_1 (typically > 220 µF) and C_4 (typically 20 µF … 100 µF) are required to ensure the basic functionality of the voltage regulator and provide protection against voltage drops in the 12 V supply system. Further elements are required to provide an EMC protection against RF disturbances and transient pulses. The diodes D_1, D_2, D_{31}, D_{32} and D_4 protect the circuit against pulses, which can occur in the vehicle supply system [5]. In addition, the diode D_2 acts as an inverse polarity protection. Capacitors C_2 and C_3 (typically 10 nF … 100 nF) are connected as close as possible to the voltage regulator, using short traces (low inductance), to supply transient current demands and act as a short circuit for fast transient pulses and RF disturbances.

From above considerations, it can be assumed that the input impedance of a typical automotive ECU is a short circuit for high frequency signals. To validate this assumption, measurements on three different ECUs from modern vehicles were performed (see Fig. 2). The input impedance of the 12V connectors was measured with a network analyzer. Due to the inverse polarity protection, the small signal impedance can only be measured with a bias voltage. This condition complies with power on state (DC on) in a vehicle.

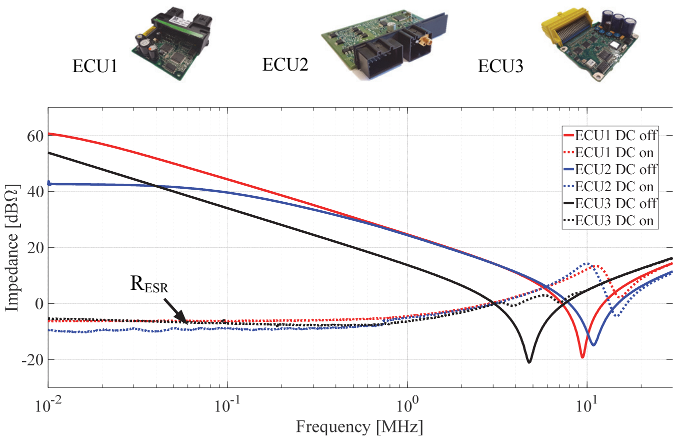

Fig. 2. Measured input impedance of three different automotive ECUs.

The results show that the 12 V input of ECUs behaves – as expected – like a low impedance under power on condition (DC on, the dotted lines in Fig. 2), which means that the short circuit assumption is reasonable. The measured impedance is only between 0.3 Ω and 6.3 Ω in the frequency range from 10 kHz up to 30 MHz when DC is on. As a result, in the further investigations complex lumped circuits for the input impedance are not taken into account. Therefor we assume the input impedance Z_{ECU} of a typical vehicular ECU as a capacitor with a typical value C=220 µF and the obtained parasitic resistance (ESR, diode resistance …) from the measurements R_{ESR}=0.3 Ω.

III. Coupling Circuits for PLC Signals

To connect the PLC modem (transceiver) to the 12 V power line, coupling circuits are required. Three types of coupling are conceivable – resistive, capacitive and inductive. The resistive coupling is not suitable, because it does not block the DC voltage. The transceiver input/output of typical communication applications, which operates in high frequency with low power are sensitive to the relatively high DC voltage of 12 V. Hence, we need to consider only the capacitive and inductive coupling.

Fig. 3 shows both variants for connecting a PLC modem to the power line. The modem is represented by a voltage source V_s with an internal impedance Z_i. The capacitive coupling (left) can be implemented with a capacitor (C_{cpl}). In combination with Z_i it forms a high pass filter. The operating frequency and the internal impedance of the PLC modem determine the choice of the capacitor value.

Due to the capacitive behavior of the ECU power input the capacitive coupling is unsuitable. The reason is that the internal impedance Z_i of a PLC modem is typically much higher than the discussed Z_{ECU}. Thus, the transmitter power is dissipated in the ECU and cannot propagate over the power lines. One solution could be increasing the ECU input impedance without increasing the DC resistance, e.g. with an inductance.

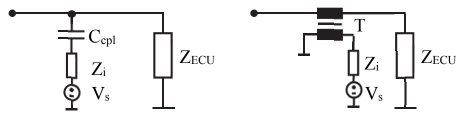

Fig. 3. PLC coupling circuits with capacitive (left) and inductive (right) coupling.

The inductive coupling (Fig. 3, right) is more favorable. A transformer (T) can be applied to transform the transmitter voltage V_s and Z_i in series to the ECU impedance (Fig. 4). By means of the transformer ratio an impedance matching can be performed to ensure maximum transmitter power insertion to the power line. After transformation, the new impedance and voltage are denoted by Z_i' and V_s' respectively.

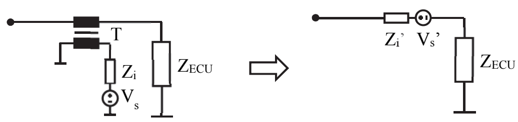

Fig. 4. Source transformation with an ideal transformer and a transformation ratio of 1.

In real applications, some aspects of transmitters should be considered like non-ideal coupling factor and the resulting stray inductance. Furthermore, the DC current in the power line can cause saturation effects in the transformer core and reduce the coupling.

The coupling circuits are in the same way applicable on the receiver side of a PLC modem. In our further investigations, we applied without loss of generality an ideal inductive coupling with a transformer ratio of 1. Coupling with a transformer seems to be more suitable in real applications, due to the flexibility of matching to the total impedance (ECU + access impedance of the power supply system) without additional circuits.

IV. Vehicular power supply topologies

In modern vehicles, ECUs are distributed over the entire vehicle body. One side of every ECU is connected to a power supply wire, and the other side directly to a fuse box or via a cable splice with other power cables. In most vehicles, the fuses for more than one ECU are merged in one fuse box. Often more than one fuse box can be found in vehicles. Such structure results in a tree topology. Two further topologies (bus and ring topology) are also possible to interconnect ECUs with the battery (Fig. 5) but are not used today in passenger vehicles.

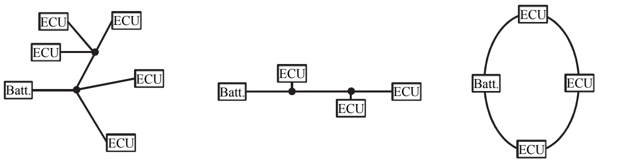

Fig. 5. Conceivable topologies to interconnect ECUs with the power supply Tree topology (left), bus topology (middle) and ring topology (right) are presented here

From communications point of view the link between two network nodes (ECUs) is characterized by its channel properties. In the tree topology, the channel characteristics can vary, due to wire length, location of fuse box, and number of cables connected to fuse box. The channel can be described by transfer functions (TF) between two nodes. Reciprocity of TFs is given in symmetrical linear systems. Therefore counting the number of TFs between two nodes is required only once. The number (M) of TFs is a function of ECU number (N) and can be calculated by the recursive formula below.

$$M(N) = M(N-1) + (N-1), \quad N \geq 2, M(1) = 1 \tag{1}$$

As shown in Fig. 6, the TF number increases rapidly with growing number of ECUs. In modern vehicles, number of ECUs exceeds 50 which results in more than 1200 TFs.

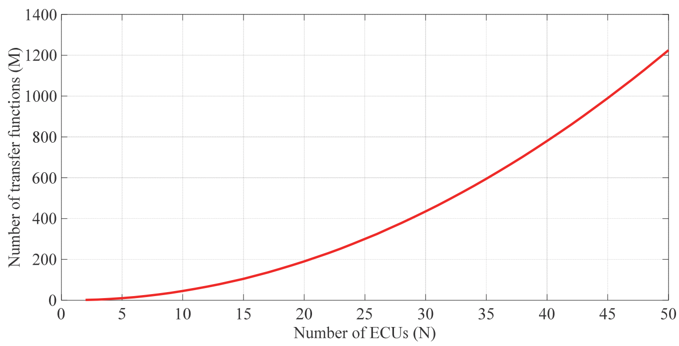

Fig. 6. Number of transfer functions as a function of ECU number in the network.

However not all channels (TFs) between the ECUs could be suitable for data transmission, due to high attenuation and distortions. Hence, analysis of the channel characteristics is required.

A. Channel Modeling

The simplest network configuration is a loaded transmission line (TL), as depicted in Fig. 7 (left). In frequency domain, the transmission line can be represented by a two-port network (right) from the well-known transmission line theory [6].

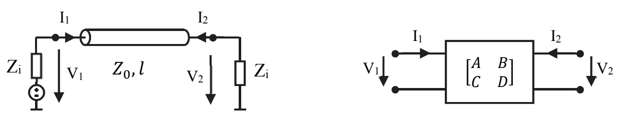

Fig. 7. Loaded transmission line (left) and two-port representation of transmission line without loads (right) by chain matrix (ABCD matrix).

The terminal voltages (V_1, V_2) and currents (I_1, I_2) of the line can be calculated with the chain matrix. In case of a lossless TL the following equation can be written:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \cos(\beta l) & -jZ_0 \sin(\beta l) \\ -j\dfrac{1}{Z_0}\sin(\beta l) & \cos(\beta l) \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}, \tag{2}$$

Where Z_0 is the characteristic impedance, l is the length and β is the phase constant of the TL. This representation allows cascading arbitrary TLs with arbitrary two port networks by simple multiplication of the chain matrices.

Connecting terminated TLs to a star point in the transmission path between transmitter and receiver (Fig. 8) leads to an additional shunt impedance in the star point.

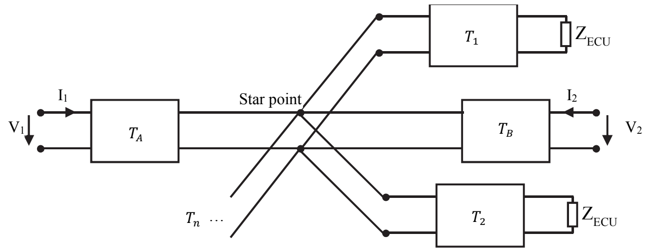

Fig. 8. Star point representation by chain matrices. Terminated TLs $T_3 \ldots T_n$ are connected between T_1 and T_2. The TLs are terminated by T_{ECU}.

The total admittance resulted from n terminated TLs can be obtained from impedance transformation and summation of individual admittances

$$Y_{sp} = \sum_{i=1}^{n} \frac{1}{Z_{0i}} \cdot \frac{Z_{0i} + jZ_{ECU}\tan(\beta_i l_i)}{Z_{ECU} + jZ_{0i}\tan(\beta_i l_i)}. \tag{3}$$

Parameters Z_{0i}, β_i and l_i are the characteristics of the i^{th} terminated TL. The chain matrix of the star point admittance is

$$T_{sp} = \begin{bmatrix} 1 & 0 \\ Y_{sp} & 1 \end{bmatrix}. \tag{4}$$

By cascading the obtained chain matrices the terminal conditions of such a star point configuration (Fig. 8) can be calculated:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = T_A \cdot T_{sp} \cdot T_B \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}. \tag{5}$$

In further analysis ECUs with PLC transceivers and inductive coupling, as described in Fig. 4, are attached to both ends of the setup. As a result of the transformation, the transmitter and receiver impedances are in series to the ECU impedance (see Fig. 4, right). Therefor serial impedance chain matrices with Z_{ECU} have to be added to Eq. (5). The chain matrix for the ECU impedance is

$$T_{ECU} = \begin{bmatrix} 1 & Z_{ECU} \\ 0 & 1 \end{bmatrix}. \tag{6}$$

Finally the transformed terminal voltages and currents can be calculated by the following equation:

$$\begin{bmatrix} V_1' \\ I_1' \end{bmatrix} = T_{ECU} \cdot T_A \cdot T_{sp} \cdot T_B \cdot T_{ECU} \cdot \begin{bmatrix} V_2' \\ I_2' \end{bmatrix} \quad (7)$$

With this equation, the channel gain between transmitter and receiver ECU can be obtained from scattering parameters with 50 Ω reference impedance by attaching 50 Ω sources to both sides.

B. *Simulation Results of vehicular Onboard Power System*

Three different topologies were investigated to analyze the influence of the ECU number (equipped with PLC modems) and star points (fuse boxes) in the tree topology of the power supply system. For this purpose TLs with Z_0=300 Ω and different lengths were applied to calculate scattering parameters for the entire network. The topologies with 3 (1 star point), 5 (2 star points) and 15 ECUs (3 star points) are depicted in Fig. 9. Topology 1 contains 3 TFs, while topology 2 and 3 gives 10 and 105 TFs.

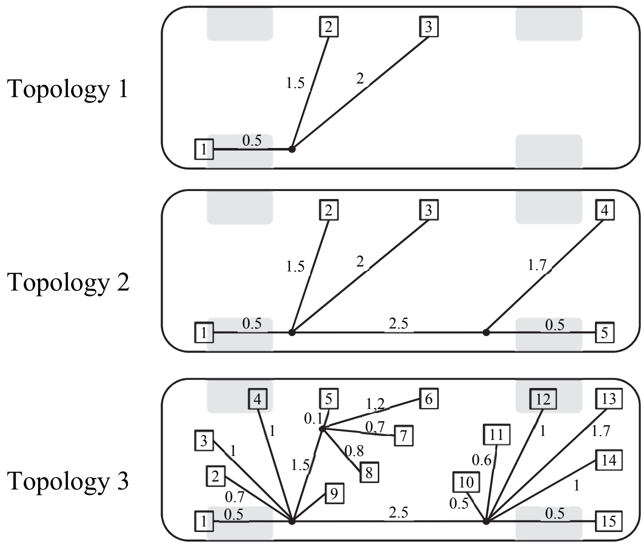

Fig. 9. Three different vehicular power supply systems analyzed

Simulations of the proposed topologies were performed in the frequency range from 150 kHz to 100 MHz. The channel gain between ECUs of topology 1 and 2 are shown in Fig. 10 and Fig. 11. Fluctuations of gain from -2 dB to -23 dB can be observed in topology 1. Furthermore, topology 2 shows similar fluctuations, but a minimum gain of -30 dB.

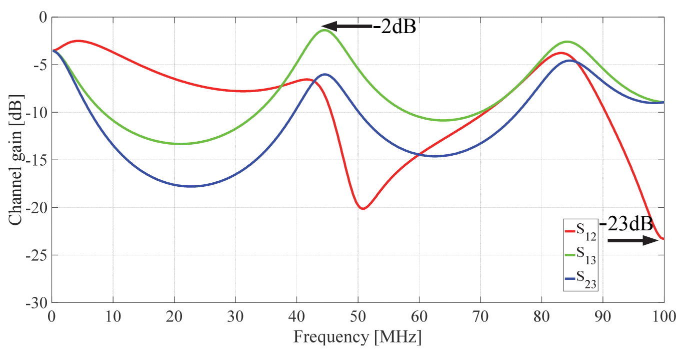

Fig. 10. Simulation results of channel gain between ECUs of topology 1.

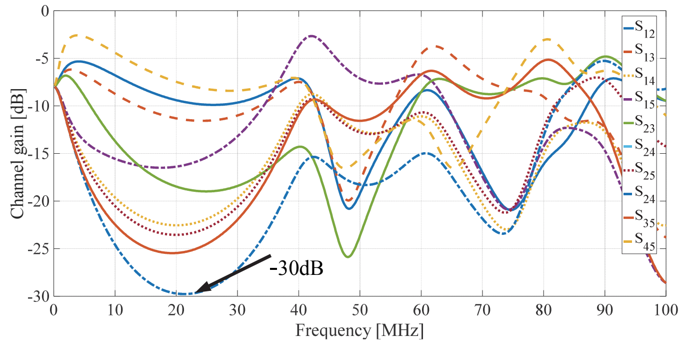

Fig. 11. Simulation results of channel gain between ECUs of topology 2.

In topology 3, the channel gain achieves a minimum of -60dB. Simulation results for best and worst transfer function are shown in Fig. 12. The worst gain $S_{6,12}$ is the same as $S_{6,14}$. This is reasonable, because in topology 3, ECU 12 has the same wire length to the same star point as ECU 14.

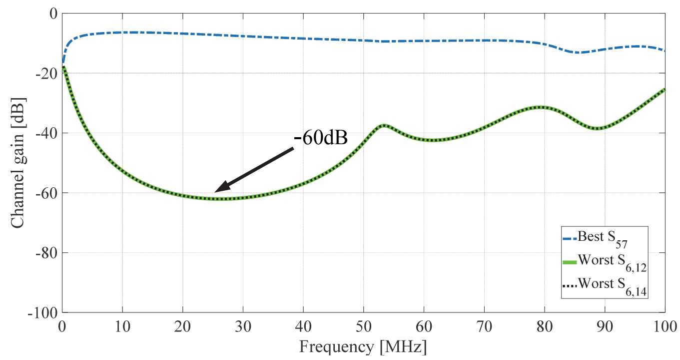

Fig. 12. Best and worst case transfer functions in topology 3

From the simulation result, it can be concluded that with increasing number of ECUs and star points the overall gain between ECUs decreases. But this behavior is not surprising. By coupling the PLC modem with a transformer, the secondary winding induces HF current flow in the power line. With increasing number of ECUs and star points, admittances are added in the path between the ECUs, which causes that the current divides at the star points and only a fraction of the inserted transmitter current arrives at the destination ECU.

High insertion loss is one challenge in such distributed networks. The other challenge is the fluctuating frequency response of the channels as a result of mismatched transmission lines and star points which will be discussed in the next chapter from communication systems point of view.

V. Discussion of Signal Integrity and EMC in Automotive PLC Systems

When evaluating the reliability of PLC data transmission, both signal integrity and restrictions of maximum RF levels in the onboard system have to be considered. For EMC the emission of the PLC modem has to be limited to ensure undisturbed operation of other components in the vehicle. The immunity of the PLC should not be violated by the noise from other devices in the supply system as well.

A. *Consideration of Signal Integrity in Narrowband and Broadband Communication Systems*

Channel characteristics, in particular amplitude and phase response, can cause a distortion of received signals. The optimal band limited channel has a flat amplitude and linear phase response. Otherwise, inter symbol interferences (ISI) can occur. As shown by simulations in IV.B, the branched structure of the supply system causes a variation of channel response in frequency domain.

Narrowband communication systems can handle such channel responses, because they allocate typically a small bandwidth. Impact of a fluctuations is slight in a narrow band of the channel and can be corrected by channel coding techniques. The investigated topologies have the most channel flatness below 40 MHz. At higher frequencies, resonances dominate the response. Equalizations techniques can compensate such fluctuating response, but are limited in real implementations by the available dynamic range.

Frequency division multiplexing (FDM) is more suitable for frequency selective channels. OFDM (Orthogonal FDM) is a usual utilized technique in broadband PLC systems [7]. It can handle variable channel response by dividing the allocated band into multiple narrow band sub channels. Break down of individual sub channels as a result of frequency selective attenuation or narrow band noise can be compensated by channel coding techniques, but results in a data rate drop. As an example we consider here the Home Plug Green PHY specifications [8] which supports data rates up to 10 Mbit/s. The operation spectrum is 2-30 MHz and 1155 sub carriers are applied with QPSK sub carrier modulation.

B. *Conducted Emission and Immunity of the PLC System*

From theoretical point of view maximum possible data rate C (in bits/s) in a noisy channel is restricted by its noise power N, the signal power P and the bandwidth $B = f_2 - f_1$. Following formula allows calculation of data rate with frequency depended signal and noise power [9]:

$$C = \int_{f_1}^{f_2} \log_2\left(1 + \frac{P(f)}{N(f)}\right) df \tag{8}$$

The data rate as a function of signal to noise ratio (SNR) is depicted in Fig. 13, to point out the impact of SNR. For the calculation, the bandwidth of 28 MHz was taken from the Home Plug Green PHY specification.

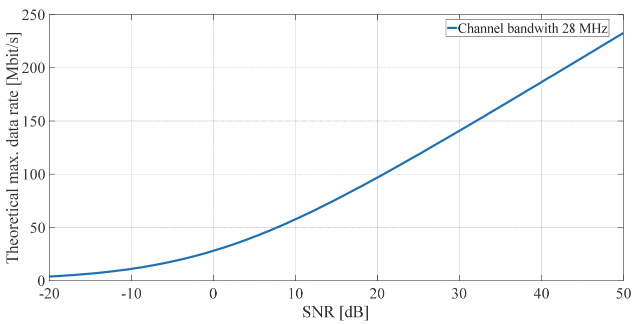

Fig. 13. Maximum data rate that can be achieved in a noisy channel as a function of signal to noise ratio with 28MHz bandwidth

In order to ensure that PLC in automotive environment is EMC compliant, operation limitations need to be found. These limitations are usually controlled and limited by EMC standards. In this work, CISPR 25 standard [10] is applied as an example to determine the limitations. Due to the current induced coupling of the PLC modem (inductive coupling specified in Fig. 4), the current limits of class 1 and class 5 with average detector and 9 kHz resolution bandwidth for conducted disturbances are applied. We determine SNR with following assumptions:

I. The noise in vehicle onboard system cannot surpass the limits specified in the standard

II. The transmitter power is assumed to be the same as class 1 limit

With assumption II, the maximum transmitter output power P_T of 9.8 dBm can be calculated for the frequency band from 2 MHz to 30 MHz using the formula:

$$P_T = \int_{f_1}^{f_2} A(f)^2 \cdot Z_i \, df \tag{9}$$

where A is current limit given in class 1.

With the determined transmitter output power and channel transfer function TF, the receiver power can be obtained. As an example Fig. 14 shows the power spectrum density (PSD) at the receivers of the ECUs in topology 1 (see Fig. 9). The dotted lines were calculated using the given current limits from class 1 and class 5. Three solid lines give the PSD of the receivers. It can be seen, that the signal level comply with class 1 limit (red dotted line), due to channel loss.

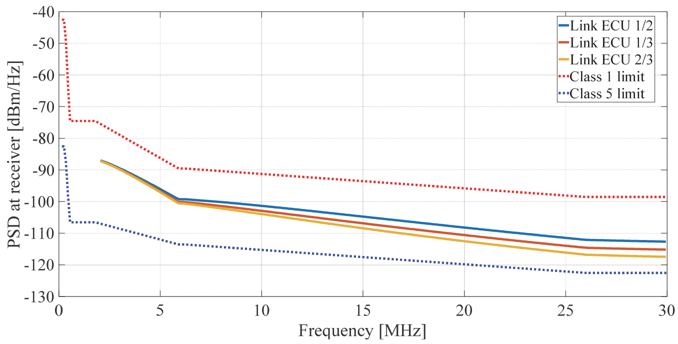

Fig. 14. Receiver power spectrum density of the receiver ECU links from topology 1 and CISPR25 class 1 and 5.

We obtain the SNR for the proposed topologies and compare it for the best and worst channel. TABLE I. summarizes the results for the receiver SNR in presence of CISPR25 class 1 and 5 noise (assumption I).

TABLE I. RECEIVER SNR [DB] IN PRESENCE OF CISPR NOISE. TRANSMITTER POWER IS APPLIED ACCORDING CLASS 1.

CISPR25 limit classes		1	5
Topology 1	Best Channel (S_{12})	-6	54
	Worst Channel (S_{23})	-11	49
Topology 2	Best Channel (S_{45})	-6	53
	Worst Channel (S_{34})	-25	34
Topology 3	Best Channel (S_{57})	-16	43
	Worst Channel ($S_{6,12}$)	-62	-2

Theoretical data rates between 251.22 Mbit/s and 32 kbit/s with SNR of 54 dB and -62 dB respectively can be achieved. As a result of increasing number of star points and ECUs, additional loads increase the channel insertion losses and reduction of SNR and consequently reduction of data rate in the vehicle onboard power system. In real transceiver implementations, the theoretical data rates cannot be achieved due to imperfect working channel coding and modulation.

VI. CONCLUSION

PLC can be attractive in automobiles. Currently the capabilities and limitations are not known. In this paper, several key issues for PLC are discussed. The 12 V input circuit and input impedance were studied and measurements of typical ECUs were presented to understand the impedance conditions in modern vehicle power system loads. It can be concluded, that terminations of the power supply system are dominated by low impedances for high frequency. Possible topologies of the power distribution system were discussed and the commonly applied tree topology was chosen for further analysis. Simulation results showed insertion loss and fluctuating transfer functions. Especially in networks with high number of ECUs and star point's high insertion loss can be expected due to mismatched terminations and additional star point impedances. Finally conducted emission and immunity of PLC modems in such onboard systems were discussed in terms of maximal achievable data rates under CISPR25 class 1 and class 5 noise limits within the frequency band of 2-30 MHz from the Home Plug green PHY specification. Theoretical data rates between 250 Mbit/s and 32 kbit/s can be achieved.

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