CHANNEL CAPACITY OF HIGH-SPEED POWERLINE COMMUNICATION IN VEHICLES

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Abstract

Powerline Communication (PLC) Systems intents to use the mains network in vehicles for high-speed data transmission. Carrier frequencies in the range of MHz are required to establish data rates of some megabits per second. In this paper, typical reference channels extracted from channel measurements are presented and computation results of their capacities according to Shannon's theorem are presented. Furthermore, the effect of limitations of frequency range and power spectral density of transmitted signal on achievable capacity is investigated. This paper outlines an assessment for theoretical channel capacity and achievable data rates of vehicular PLC transmission schemes. Finally, EMC (Electromagnetics Compatibility) constraint according to CISPR 25 (Comite International Special des Perturbations Radioelectrique – The International Special Committee on Radio Interference) is deeply considered.

Keywords: vehicular PLC, noise, channel capacity, data rates, EMC.

1. Introduction

Networking of electronic components inside of vehicle sets great challenges to the network system in the future. Its architecture will play an important rule in the future in addition to software and hardware deployed. Making use of electricity lines for an integrated transmission of energy and data is one of promising networking concepts for the future internal vehicular communication system.

This idea came from the concept of in-house networking, which is a part of technology transferring data through low voltage distribution cables well-known as powerline communication. Since middle of May 2001 the commercial internet connection through wall-socket with data rate of 2 Mbps became reality. This success story tends to be adopted by transportation system, especially vehicles. Such networking method makes data cables unusable and therewith reduces the vehicles weight and production costs significantly. A new method of electric lines conditioning has given the possibility to realize high speed data transmission of 10 Mbps through copper lines.

The goal of this contribution is to deliver the theoretical channel capacity, which is according to Shannon's theorem depending on usable frequency range and signal-to-noise ratio. These parameters are confined by the low-pass characteristics of cable, frequency-selective fading by means of multi-path signal propagation and the additive noises.

Transfer function of channel and noise spectra are characteristic quantity of transmission line and can be obtained by measurement. The spectrum of transmitted signal in PLC should be chosen so that it could be compatible electromagnetically, especially with electronic components inside of vehicles.

This paper presents the computation result of channel capacity and achievable data rate for broadband PLC System. In section II, the characteristics of channel as the most important information for computing the capacity and system design will be introduced. In section III, the corresponding basic theory, including the optimizing method 'water pouring' will be briefly reviewed. Section IV discusses the results of computation. Here, coherent QAM (Quadrature Amplitude Modulation) is considered as modulation scheme, which is an important part of an adaptive OFDM (Orthogonal Frequency Division Multiplexing). The last section considers the EMC aspect of system and its constraint to maximal achievable capacity and data rate in respect of established regulation.

2. Experiment

In order to use high-frequency range for data transmission the cable topology must be new conceived.

Here, the make use of twisted pair cable is introduced [1]. Twisting the cable leads to increased isolation strength, because it reduces the impairment caused by common-mode currents. In the same time, this effort diminishes emission effect to outer environment.

Furthermore, the employment of cable structure in the form of star is recommended to guarantee an identical transmission among subscribers. However, in such topology, numerous signal reflections at star-points are generated and this leads to frequency-selective fading in the transfer function. To solve this problem a so-called modified star-points is introduced [1], in which a core ferrite having double holes is applied to every outgoing lines. This method makes the star point matched to line impedance of twisted cable in high-frequency range, without influencing the low-frequency behavior of board-network.

The signal coupling into powerline takes place inductively by means of ferrite. To avoid penetration of high-frequency signal into vehicles components as well as its unwanted emission effect, condensators are deployed inside of ferrite, which takes effect as high-frequency short-circuit.

Figure 1 depicts the new art of board network consisting of three star-points [2]. This structure can connect maximal 36 components and is easily expandable.

Additive noises on broadband powerline communication channels can be classified specifically into three main types: impulsive noise, short-time noise, and quasi-continuous noise [1]. Impulsive noise is produced by switching operation in electronic components. Its sequence can change intensively. Figure 2 shows patterns of impulsive noise arisen from certain switching operations [2].

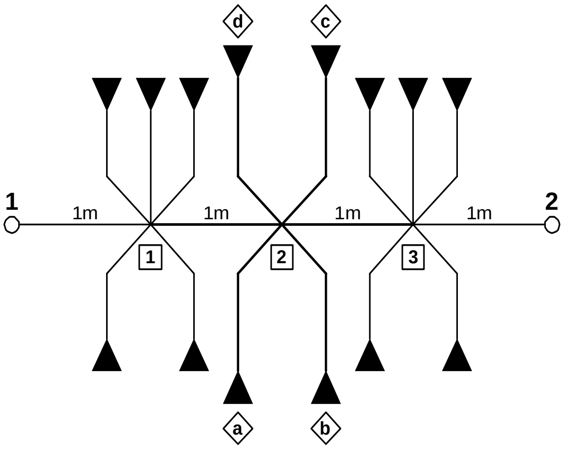

Figure 1. New structure of board network of vehicle[2]

Short-time noise is defined as noise occurred with duration of about 10 seconds. Such noise is produced by certain motor activities, e.g. sit-displace or window-raising. Figure 3 presents its spectra [2].

Quasi-continuous noise has duration of a few minutes or hours, e.g. light, air-conditioner or motor-running. Figure 4 show the measurement resulting from scenario motor-running idle [1]. All measurement took place on Audi A6.

All measurements exhibit concisely, that the levels of three measured noises decline significantly in frequency range after 150 MHz. Therefore, the vehicular PLC System is suitable to work over this favorable range, so that the realization cost will be reduced significantly.

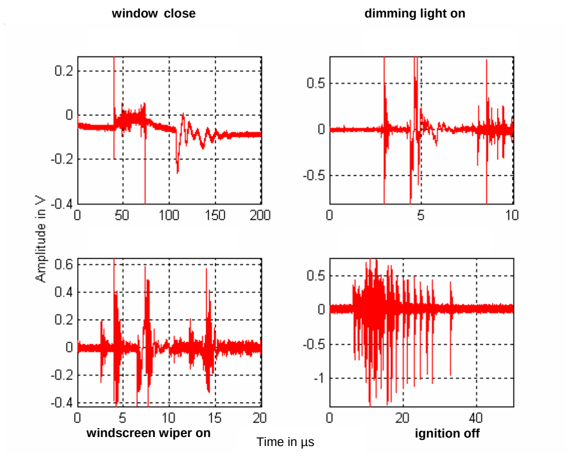

Figure 2. Measured impulsive noise[2]

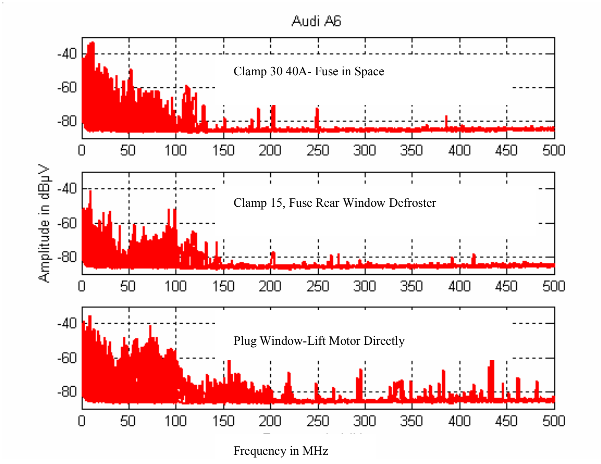

Figure 3. Measured short-time noise[2]

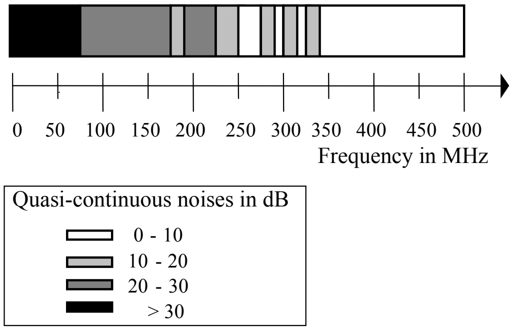

Figure 4. **Measured quasi-continuous noises[1]**

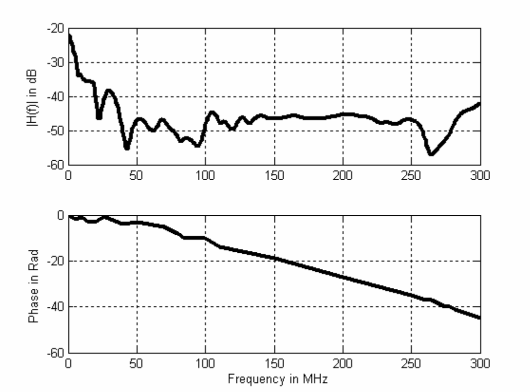

Figure 5. **Measured transfer function of new board Network[1]**

In addition to that, white background noise, which arises from summation of numerous noise sources, takes place on the channel. The average level of its power spectral density constitutes about -136.9897 dBV^2/Hz [1].

To compute channel capacity only two noise types are taken into account, i.e. background and quasi-continuous noises. The other ones are neglected because of their short-time presence.

By measuring transmission line between end-points 1 and 2 on the new board network described in subsection II.A, one obtains the transfer function showed in Figure 5 [1].

It is clear that the frequency range between 150 MHz and 250 MHz offers nearly constant attenuation and linear phase characteristics. In this range, signal experiences relative modest distortion. This give advantage in realization communication system. In this case, the high attenuation level is not of disadvantage, because noises are attenuated as well as signal. This channel characteristics will serve

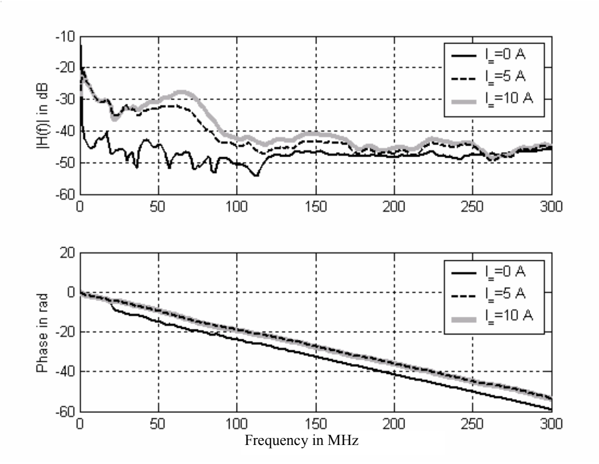

Figure 6. **Measured transfer function in presence of direct-current loading[1]**

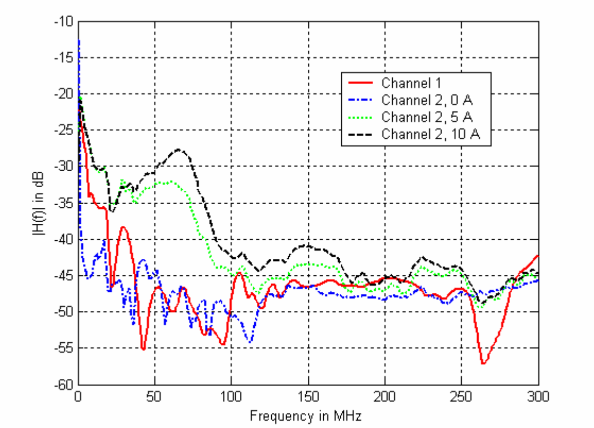

Figure 7. **Transfer function of first group of reference Channels[1]**

A main problem occurs if data come into an active subscriber, whose activities generate impulsive noise destroying the incoming data. Such noise does not experience the attenuation. The possible solution is to synchronize subscriber and integrated transmitter/ receiver.

In vehicles, direct-current loading occurs frequently. Its influence to the channel characteristics can be observed in Figure 6 [1].

It is again obvious that nearly constant attenuation and linear phase extend between 180 and 220 MHz for all case.

As first group of reference channels, the channel 1 and 2 are introduced. Channel type 2 demonstrates channel characteristics depending on direct-current loading as showed in Figure 7 [1].

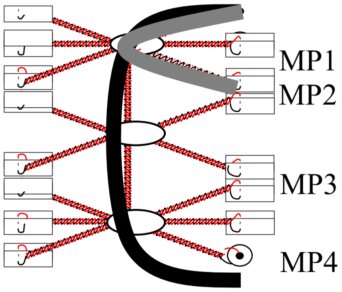

Figure 8. Measurement of second group of reference channel [2]

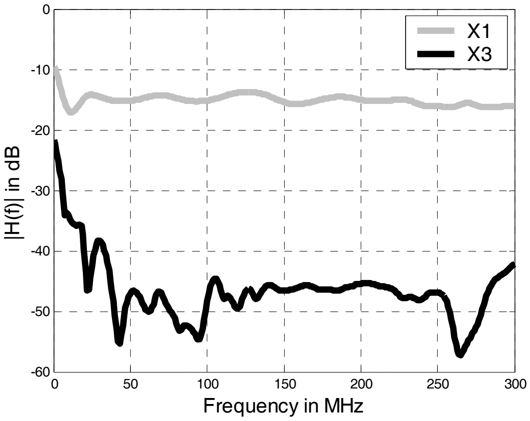

Figure 9. Transfer function of second group of reference Channels[1]

The second group of reference channels are obtained from measuring lines in the way demonstrated in Figure 8 [2]. It is of interest to investigate the channel characteristics depending on star-points included by measured lines and their corresponding capacities. Figure 9 show that the line containing three star-points (X3) has much higher attenuation and is more frequency-selective as those with one star-points (X1) [1].

The Shannon's theorem delivers the theoretical maximal achievable capacity over disturbance channel without considering modulation scheme [3]. The capacity of a channel of bandwidth B, which is distorted by gauss distributed noise of power S_N and transferring data signal of received power S_E, can be estimated by

$$C = B \cdot ld\left(1 + \frac{S_E}{S_N}\right) \quad \text{[bps]} \tag{1}$$

If the channel depends on frequency with power spectral density (PSD) of noise $S_{NN}(f)$ and of received data signal $S_{EE}(f)$, the channel capacity can be calculated by integration over frequency range inside of bandwidth B.

$$C = \int_{f \in B} ld\left(1 + \frac{S_{EE}(f)}{S_{NN}(f)}\right) df \tag{2}$$

The received data signal can be obtained from transmitted signal PSD $S_{SS}(f)$ and amplitude of transfer function $|H(f)|$

$$C = \int_{f \in B} ld\left(1 + \frac{S_{SS}(f) \cdot |H(f)|^2}{S_{NN}(f)}\right) df \tag{3}$$

The channel capacity can be affected by varying transmitted signal PSD $S_{SS}(f)$. In practical system, $S_{SS}(f)$ is confined to S_{max}. The channel capacity could be maximum, if $S_{SS}(f)$ is distributed according to so-called Water-Pouring Method [4] with equation

$$S_{ss}(f) = \begin{cases} S_{\max} - \dfrac{S_{NN}(f)}{|H(f)|^2} & f \in B \\ 0 & f \notin B \end{cases} \tag{4}$$

with precondition

$$S_s = \int_{f \in B} \left[S_{\max} - \frac{S_{NN}(f)}{|H(f)|^2} \right] df \tag{5}$$

In real case, the data of measured channel extend over discrete frequency points with constant distance Δf. To estimate the channel capacity in this case, an approximation on capacity of subchannels with constant amplitude of transfer function is introduced. For this purpose sampling frequency f_i is defined as center frequency of subchannel i.

$$f_i = i \cdot \Delta f \tag{6}$$

This consideration is taken into account to calculate the channel capacity over discrete frequency range

$$C = \Delta f \sum_{\substack{\forall i \\ fi \in B}} ld\left(1 + \frac{S_{SS}(f) \cdot |H(f)|^2}{S_{NN}(f)}\right) \tag{7}$$

To determine the probability of error for QAM, the signal point constellation must be specified. Each QAM signal point consists of q bits. Pairs of them are separated with minimum Euclidean distance Δ.

Assuming that all signal points are equally probable, the average transmitted power P is evaluated by

$$P = \frac{1}{6}\Delta^2\left(2^q - b\right) \tag{8}$$

where $b = \begin{cases} 1 & if\ q\ even \\ 0.5 & if\ q\ odd \end{cases}$

QAM signal is now superposed by additive white gaussian noise $\gamma = \varsigma + j\cdot\xi$ of variance σ_R^2. The probability of symbol error may be expressed by

$$P_S \le 1 - P\left\{|\varsigma| < \frac{\Delta}{2}\right\}P\left\{|\xi| < \frac{\Delta}{2}\right\} \tag{9}$$

and yields

$$P_S \le 1 - erf^2\left(\sqrt{\frac{3}{2}\frac{1}{2^q - b}\frac{P}{\sigma_R^2}}\right) \tag{10}$$

where $erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt$

Furthermore, it is interesting to determine achievable maximum data rate in dependence of SNR (Signal to Noise Ratio) if the probability of symbol error may not exceed a certain level. For this purpose the inverse of the error function $y = erf(x)$ is defined by $x = \Psi(y)$ to obtain term 2^q .

$$2^q = 1 + \frac{3}{2}\psi^{-2}\left(\sqrt{1-P_S}\right)\cdot\frac{P}{\sigma_R^2} \tag{11}$$

The achievable bit rate in bit per dimension is calculated by $R' = 0.5 \cdot ld\,(2^q)$ and yields

$$R' = \frac{1}{2}ld\left(1 + K\left(P_S\right)\cdot\frac{S_E}{S_N}\right) \tag{12}$$

with $K\left(P_s\right) = \frac{3}{2}\psi^{-2}\left(\sqrt{1-P_s}\right)$ and $\frac{S_E}{S_N} = \frac{P}{\sigma_R^2}$

This expression differs from the capacity of the AWGN (Aditive White Gaussian Noise) - channel only by the factor $K(Ps)$

In real QAM signal constellations only integer number of q are possible. The continuous solution of (12) is rounded down to the next smaller integer. This method is realized by an adaptive OFDM-System, in which the constellation of each subchannel is matched to its known SNR.

$$R_i' = \left\lfloor R_{i,cont}' \right\rfloor = \left\lfloor \frac{1}{2}ld\left(1 + K\left(P_s\right)\frac{S_{SS}(f)\cdot\left|H(f)\right|^2}{S_{NN}(f)}\right)\right\rfloor \tag{13}$$

The total bit rate obtained from summation bit rate of all subchannels over spectrum is computed by

$$R = 2\Delta f\sum_{i=1}^{N} R_i' \tag{14}$$

3. Result and Discussion

Referred to equations (3)-(5), the channel capacity could maximum, if the transmitted signal PSD is so distributed that the frequency range with lower attenuation or smaller noise PSD will be assigned with higher transmitted signal PSD. In the practice, this can be realized with an adaptive OFDM technique distributing transmitted signal power to several subchannels. Alternatively, the transmitted signal power could be also homogeneous distributed over the assigned frequency range. This technique is very simple to realize, but leads to greater power losses.

To compare the estimated channel capacity in different cases, the transmitted signal power $P_S = 1\ V^2$ is applied. Because the impedance of board network is varying with frequency, a physical power could not be general given. For this purpose, an impedance of 50 Ohm is taken as reference to correspond a physical power of 20 mW. To estimate the channel capacity, two ranges of spectrum are considered, i.e. spectrum A between 0 and 300 MHz, and spectrum B between 170 and 220 MHz. In these ranges the transmitted signal power are distributed homogenous (index 1) and optimal with Water-Pouring method (index 2) onto subchannels with each bandwidth 1 MHz as listed in Table 1.

It is of interest to compute capacity and data rate of each spectrum type in presence of background and motor noise or only one of them on two reference channel groups.

The Figure 10 show the difference between case of homogenous and of optimal transmitted signal PSD in spectrum A on channel type 1 of first channel group. Here, only noise from motor-running is considered.

Table 1. Spectra of transmitted signal

Spectrum	***B*** **in MHz**	**P_S in V²**	**Method**
A_1	300	1	homogenous
A_2	300	1	water-pouring
B_1	50	1	homogenous
B_2	50	1	water-pouring

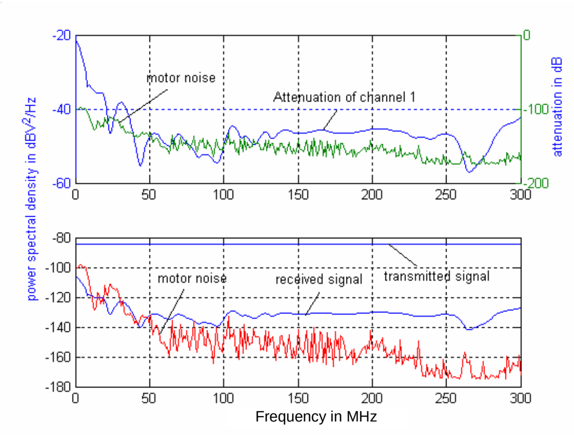

Figure 10. Homogenous transmitted signal on channel 1 with motor-running noise

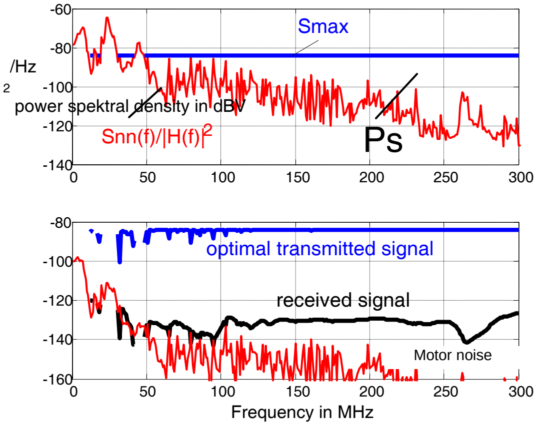

Figure 11. Water-Pouring-Method signal on channel 1 with motor-running noise

In Figure 11, it is obvious, how the water-pouring works. Subcarries with poor SNR are assigned with low transmitted signal power. In extreme case, no power is distributed for subchannels with negative SNR. In this case, the transmitted signal PSD is maximum and higher about 0.97 dB from -84.771 dBV^2/Hz to -83.803 dBV^2/Hz. The channel capacity also increased about 1.6% from 1,037.90 Mbps to 1,054.10 Mbps.

Figure 12 presents the density of corresponding channel capacity as well as continuous and discrete data rate.

All results of calculation are presented in Table 2 and Table 3. The unit is in Mbps. The increasing capacities as well as data rate on channel type 2 come along with the decreasing attenuation by increasing direct-current loading.

Table 2. First channel group on motor-running-noise channel

(a) Channel capacity

Spectrum	**channel 1**	**channel 2, 0 A**	**channel 2, 5 A**	**channel 2, 10 A**
A_1	1,037.90	1,026.70	1,236.20	1,321.90
A_2	1,054.10	1,046.60	1,245.40	1,331.40
B_1	269.33	253.59	264.43	275.24
B_2	269.32	253.57	264.41	275.23

(b) Data rate

Spectrum	**channel 1**	**channel 2, 0 A**	**channel 2, 5 A**	**channel 2, 10 A**
A_1	567	558	717	801
A_2	602	598	743	811
B_1	172	160	171	180
B_2	173	160	171	181

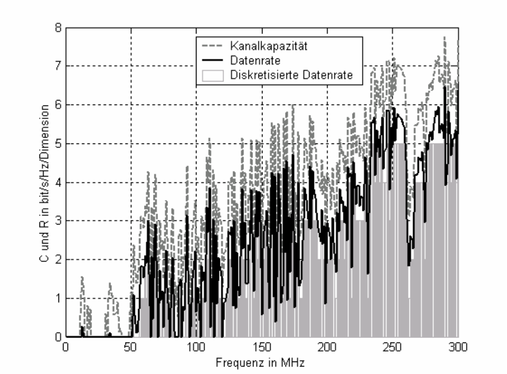

Figure 12. Density of channel capacity and data rate

Table 3. Second channel group on motor-running-noise channel

(a) Channel capacity

Spectrum	**channel X1**	**channel X3**
A_1	2,549.7	1,037.9
A_2	2,549.8	1,054.1
B_1	527.37	269.33
B_2	527.37	269.32

(b) Data rate

Spectrum	**channel X1**	**channel X3**
A_1	1,983	567
A_2	1,991	602
B_1	430	172
B_2	430	173

Meanwhile, the second channel group exhibits the higher capacities as well as data rate on channels X1 and X2, which have better channel characteristics because of relative shorter lines and less star-points included.

Addition of background noise of -136.9897 dBV^2/Hz to the previous case leads to following result showed in Figure 13.

Table 4 show the Water-Pouring increased the maximal transmitted signal PSD from -84.771 dBV^2/Hz to -82.692 dBV^2/Hz as well as the capacity by 6.4% from 256.558 Mbps to 273.016 Mbps. Addition of background noise led to the significant capacity reduction up to one-fourth.

The computation of capacity for the second channel group in this noise scenario gives the following results (Table 5).

Furthermore, the capacity for channel without motor noise is investigated (Table 6). For the second channel group, the results are as following (Table 7).

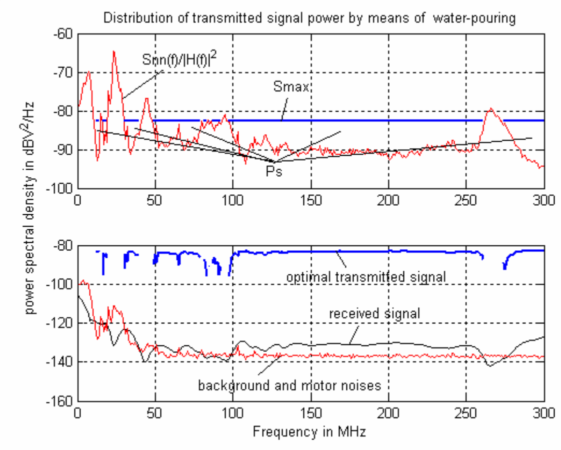

Figure 13. Water-Pouring-Method on channel 1 with additional background noise

Table 4. First channel group on channel with motor and background noise

(a) Channel capacity

Spectrum	channel 1	channel 2, 0 A	channel 2, 5 A	channel 2, 10 A
A_1	256.55	240.50	421.04	498.61
A_2	273.01	256.16	429.02	507.25
B_1	116.46	101.46	111.77	122.17
B_2	116.45	101.44	111.74	122.15

(b) Data rate

Spectrum	channel 1	channel 2, 0 A	channel 2, 5 A	channel 2, 10 A
A_1	0	0	39	76
A_2	4	0	70	101
B_1	48	0	22	50
B_2	44	4	21	49

Table 5. Second channel group on channel with motor and background noise

(a) Channel capacity

Spectrum	channel X1	channel X3
A_1	1,702.4	256.56
A_2	1,702.4	273.02
B_1	373.09	116.46
B_2	373.09	116.45

(b) Data rate

Spectrum	channel X1	channel X3
A_1	1,087	0
A_2	1,091	4
B_1	295	48
B_2	295	44

Table 6. First channel group on channel with only background noise

(a) Channel capacity

Spectrum	channel 1	channel 2, 0 A	channel 2, 5 A	channel 2, 10 A
A_1	354.90	303.58	544.87	622.00
A_2	362.15	305.29	545.83	622.68
B_1	117.59	102.57	112.89	123.30
B_2	117.59	102.56	112.87	123.29

(b) Data rate

Spectrum	channel 1	channel 2, 0 A	channel 2, 5 A	channel 2, 10 A
A_1	35	4	106	148
A_2	62	16	165	182
B_1	50	0	24	50
B_2	48	0	23	50

Table 7. Second channel group on channel with only background noise

(a) Channel capacity

Spectrum	channel X1	channel X3
A_1	1,850.9	354.90
A_2	1,850.9	362.16
B_1	374.27	117.60
B_2	374.27	117.59

(b) Data rate

Spectrum	channel X1	channel X3
A_1	1,206	35
A_2	1,207	62
B_1	300	50
B_2	300	48

In the first group, the Water-Pouring worked well in the spectrum A, which has frequency selective characteristics in range up to 100 Mhz. Therefore, this method deliver no gain for capacity increase in the spectrum B. In some cases even the optimizing process reduced the channel capacity slightly. This occurred due to losses in calculation process.

In the second group, the channel X1 and X2 are nearly not frequency selective. Therefore, it is not of advantage to deploy the Water-Pouring. Beside that, they exhibit the capacity two-three times than of the channel X3 in the spectrum B, in which the PLC System is designed to operate.

In this subsection, the dependence of capacity on some important parameters is investigated. Firstly, the influence of SNR on the channel performance from receiver point of view is investigated. For this purpose the reference channels are normalized. As shown in Figure 14, the channels in first group has much less capacity density in comparison to an ideal distortion free channel because of their high attenuation.

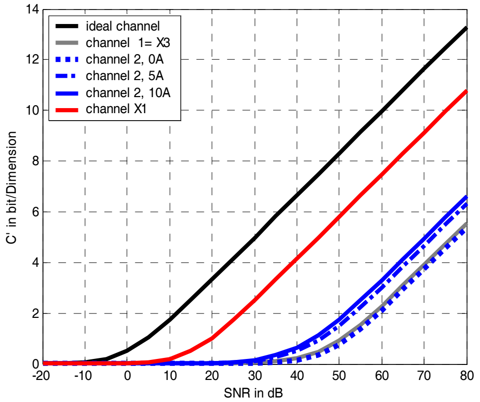

Figure 14. Capacity of normalized reference channels

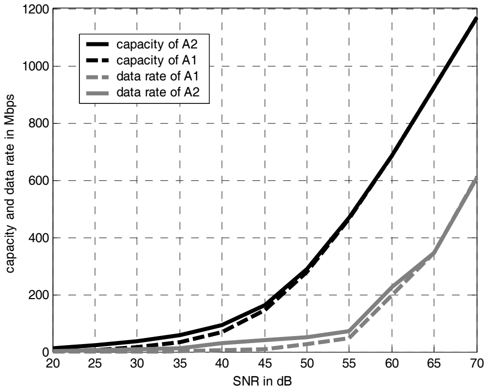

Figure 15. Capacity and data rate in dependence on signal-to-noise ratio

Figure 15 shows the channel capacity and data rate in spectrum A in dependence on SNR with background noise as the sole noise on the channel 1. It is obvious that higher gain is achieved by optimal distributed transmitted signal power in poorer SNR. On channel with high SNR, optimizing method approximates the performance of homogenous distribution. Figure 16 show the channel capacity in dependence on transmitted power.

The reduction of used bandwidth is obvious in this case. The capacity difference between spectrum A and B is greater continuously with higher transmitted signal power. This proves the Shannon's theorem, which considers bandwidth as the most important resource. The appearance of motor-noise contributes disadvantageous to the reduction of channel capacity, for example, up to about 50% in spectrum B.

The investigation of data rate in dependence of symbol error possibility deliver the result showed in Figure 17. Data rate is decreased with poorer symbol error possibility. It is of interest, that data rate increase significantly in spectrum B in noise environment without motor-noise, because of not frequency selectivity in this range.

To investigate the influence of amounts of used sub carriers on channel capacity the amounts of sub carriers in spectrum A are step-by-step increased from 300 to 4800. Figure 18 shows the result.

It is clear, that the channel capacity remains constant over the amounts of sub carriers. Here it is clearly, that the optimization brings only small gain, especially in case of no additive motor-noise.

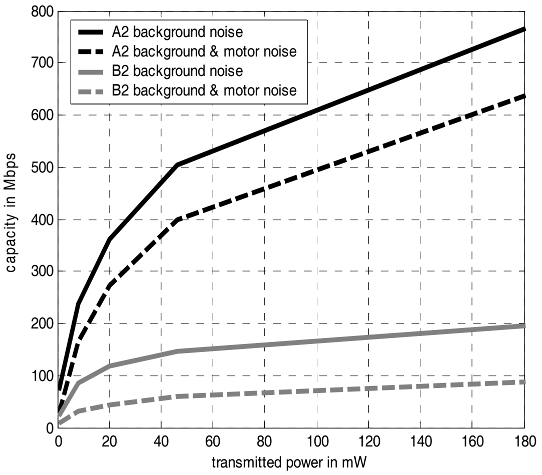

Figure 16. Channel capacity in dependence on transmitted power

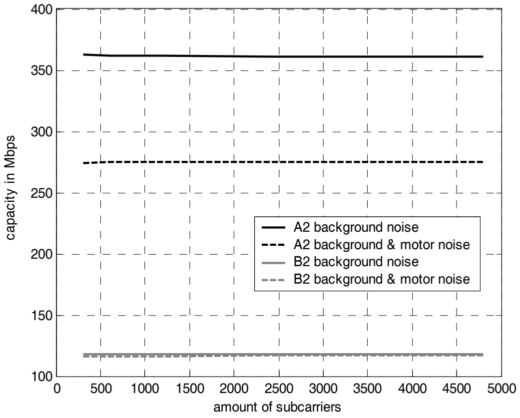

Figure 17. Data rate in dependence on symbol error possibility

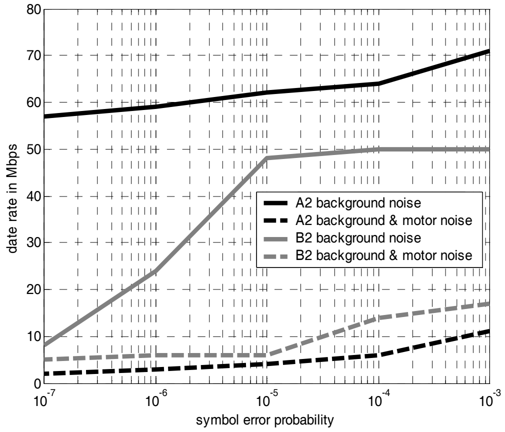

Figure 18. Capacity in dependence on the amounts of sub carriers

While transmitting signal at high-frequency over cables, a wiring system may operates as antenna [3]. It may emit radiation considerably due to the lack of symmetry. Electromagnetics interference (EMI) with other electronics components inside of vehicle and high-frequency services in the same frequency range may occur.

To enhance its EMC two efforts are regarded.

- Twisting cables to provide a good isolation as described in subsection II.A.
- Keeping transmitted signal power on maximal permissible level according to existing regulations, e.g. CISPR 25.

CISPR 25 allows a maximal level of broadband noise of 28 dBμV by peak-detection using filter bandwidth of 120 kHz measured at antenna terminal [4]. Here, the vehicular PLC system can be regarded as source of broadband noise. In measurement took place in firm Bosch an injected power of 70 dBμV into PLC wiring system generated noise power of 30 dBμV at antenna terminal. By taking attenuation of car bodywork of 30 dB into account, a maximal permissible transmitted power spectral density of -72 dBV^2/Hz approximately can be obtained.

The following tables show the estimated maximal achievable channel capacity and data rate in respect to CISPR 25 with the presence of background and motor noises.

In comparison to the Table 4 one can see that the increase of power spectral density about 12 dB in spectrum A makes the capacity higher up to three times.

For the second channel group, the results are as shown in Table 8 and 9.

Table 8. First channel group

(a) Channel capacity

Spectrum	**channel 1**	**channel 2, 0 A**	**channel 2, 5 A**	**channel 2, 10 A**
A_1	783.81	756.56	1,002.8	1,087.9
A_2	786.40	765.65	1,002.8	1,088.1
B_1	156.91	141.39	152.06	162.75
B_2	156.91	141.38	152.06	162.75

(b) Data rate

Spectrum	**channel 1**	**channel 2, 0 A**	**channel 2, 5 A**	**channel 2, 10 A**
A_1	240	245	453	549
A_2	254	245	472	552
B_1	50	50	50	59
B_2	50	50	51	61

Table 9. Second channel group

(a) Channel capacity

Spectrum	**channel X1**	**channel X3**
A_1	2,336.1	783.81
A_2	2,336.0	786.40
B_1	414.53	156.91
B_2	414.53	156.91

b) Data rate

Spectrum	**channel X1**	**channel X3**
A_1	1710	240
A_2	1708	254
B_1	300	50
B_2	300	50

4. Conclusions

In this contribution, the new structure and conditioning method of cable in vehicle is proposed to make possible the integration of energy and data transmission. By using ferrite in each star point, the networks can achieve a good matching to exhibit high channel capacity and in the same time, the low-loss energy supply for all subscribers is guarantee.

The frequency range between 180 and 220 MHz is proposed for future use because of nearly constant attenuation and linear phase and independence on direct-current loading. This simplifies the design of a high-speed communication system. Beside that, the placement of application media must consider their data rate requirement. Two equipment exchanging data with rate beyond 100 Mbps should be connected to cable having up to two star-points.

Theoretical investigation revealed, that the new conceived vehicular wiring system exhibits channel capacities in the proposed operating spectrum beyond 100 Mbps. Meanwhile, experimental investigation proved that data rate of 10 Mbps has been realized by using incoherent DBPSK as baseband modulation schemes.

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