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Statistical Analysis of the Power-Line Channel Noise Characteristics in the Frequency Domain

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Abstract-In this paper we are studying the power line channel noise in the frequency domain. The noise is measured using a spectrum analyzer. The channel noise profile is essential when OFDM is applied. Moreover, noise measurements are statistically processed in order to extract the probability density functions of the noise power for more than 120 different frequencies in the frequency range 1.15MHz-30MHz. The probability density functions of the noise power spectrum density are dominated by the impulsive components of the noise and they could be a useful tool to estimate the capacity of the power line channel when OFDM is applied.

Key-Words: -Power-line channel noise-model, OFDM system

1 Introduction

Power lines provide a hostile environment for communication signals. However, as the knowledge of their characteristics increase new methods are invented to counterbalance the problems. After so many years of systematic efforts researchers are convinced that Orthogonal Frequency Division Multiplexing (OFDM) is an appropriate candidate for data transmission over power lines. OFDM is very resilient when a communication link suffers from great delay spread [1]. Delay spread is a major problem over power lines [2].

OFDM is the parallel transmission of data over subchannels separated in the frequency domain. When OFDM is applied it is essential to know the subchannel characteristics at the frequencies of interest. A channel model that describes the subchannels' noise characteristics is of major importance, as based on that the bit load per subcarrier can be calculated and additionally, the probability of error of a multicarrier system can be determined. This noise model is the aim of this study. The models are obtained after statistical processing of the data acquired during a great measurements campaign since 2001 [3-4]. The results verify already known characteristics and provide new substantive information on the power line channel. The data are obtained in the frequency domain.

There are several attempts in the past trying to estimate the power line capacity [3], [5]. Those attempts did not approach the problem correctly due to the lack of a complete statistical power line channel model. For instance, the capacity was calculated based on average values of the noise power $E[n^2]$ per frequency. Those values are sufficient when the noise model is gaussian. However, the noise has been proved that is not gaussian [6]. Another approach is to calculate the best or worst noise scenario and calculate extreme levels of capacity [6]. Hence, a communication system that accomplishes to work for the worst noise scenario is ensured that it can work properly under all noise circumstances. However, such an approach should be accompanied with a study concerning the period of time that the channel suffers from the worst scenario. Otherwise, there is a waste of resources because the system does not exploit the current channel's condition, which may be better compared to the worst case.

The power-line channel noise consists of several types of noise due to the different nature of the noise sources. The power line modems have to confront the superposition of all those components that affect the communication signal. There are noise components having a power level that is variant, in terms of seconds, minutes or hours and characterized as colored gaussian background noise. On the other hand there are noise impulses periodic, synchronous or asynchronous to the mains frequency, and non-periodic asynchronous [7]. When impulsive noise hits its magnitude is greater than background noise.

Thus, impulsive noise is dominant and causes the greater problem to a communication system. Impulsive noise is parameterized by its amplitude, width and interarrival time. All of them are parameters in the time domain. Nevertheless, when OFDM is applied it would be of great importance if its characteristics are examined in the frequency domain.

In this study we confront the noise as a superposition of its components in the frequency domain. Particularly, we are trying to investigate the specific characteristics that the noise presents in each frequency and create a noise model that is dependent on frequency. Since a general noise model is the target, a great number of samples per frequency is gathered. The noise samples are collected through different hours a day and different days of the years that the measurements campaign lasted. The noise models are extracted and presented for the first time at the best of the authors' knowledge. The paper is organized as follows. In section 2 the noise characteristics are explained. Particularly in section 2.1 the well-known power-line noise components are repeated here for quick reference. Then in section 2.2 the power-line noise sample characteristics are presented in the frequency domain. It is one of the contributions of the paper the indication of the periodicity that the correlation coefficient present between any two distinct in the frequency, noise samples. In section 3 the probability density functions are presented for 124 different frequencies. These parameters are the constituents of the complete noise model of the noise samples in the frequency domain. This is also a novel contribution of the paper. Then in section 4 the validity limits of the models are discussed and the paper concludes in section 5 with some general remarks and proposals for further work.

2 Noise Characteristics

2.1 Power line noise components

The power line noise components have been determined in several papers [2], [7], [8], [9]. According to the measurement techniques and technical equipment available there were detected three, four or five components in the literature. Nevertheless, all of them deduce that there is a background noise component (such as colored Gaussian and narrowband noise due to radio stations transmitting in frequencies less than 30MHz) and impulsive noise either periodic (synchronous or asynchronous to the mains frequency) or non-periodic asynchronous. From a telecommunications point of view the power line receiver is affected in the time domain from the superposition of all those noise components. When OFDM is applied for data transmission it would be important to know the noise characteristics in the frequency domain as in fact OFDM is the transmission of data through parallel orthogonal frequencies. Hence, the noise components described in the literature in the time domain should be identified in the spectrum and quantify their effect in every frequency. This is exactly the main target of this paper.

2.2 Power-Line Noise Sample Characteristics

The noise power spectral density is measured using a spectrum analyzer. An automatic measurements set up was used. Special care was taken to equalize "a-posteriori" the attenuation of the noise samples passing through the filter and the isolation transformer before entering the front end of the spectrum analyzer. The frequency range of interest was swept and noise samples were transferred from the spectrum analyzer to a computer's hard disk. The measurements took place in the lab and in an apartment during several different hours per day.

A great number of noise samples were collected. The noise samples from 1.15MHz up to 30MHz are shown in Fig. 1. The noise level has a great deviation. It is strongly dependent on three parameters. The time of the day that the measurements are carried out, the place of the measurements and the frequency. The time of the day has to do with the human activity. The place has to do with the appliances that are connected and in use i.e. in-house, laboratory and industrial area. Finally, when noise is injected to the power lines, it is attenuated with the frequency increase. Moreover, the frequency bands where there are radio stations will present high noise levels.

The best and worst noise scenario is the lower and upper envelope of Fig. 1. Generally, the noise is stronger in the lower part of the frequency band.

Since the noise has a great variance and dependence from time and place the extraction of average values has no practical interest as those values will be dependent on time and place. Hence, statistical noise models are necessary.

It is interesting to find out whether the noise samples

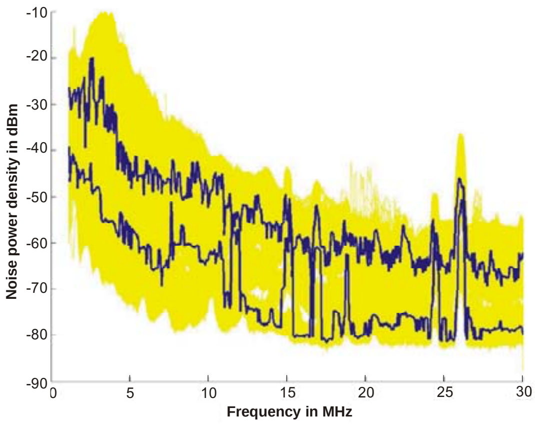

Fig. 1. Noise samples measured in the lab and in house. The upper and the lower envelope is the worst and the best noise measured scenario. The lower dark line is the average gaussian noise component and the upper dark line is the average impulsive noise component.

belonging to different frequencies are statistically independent or not. The noise samples at two different frequencies were considered as two variables and the sweeps as observations. The average correlation coefficient for every pair of variables that differ one frequency step (i.e. 240.4KHz for our experiments) has been calculated. The same calculations were made for those variables that differ two steps, three steps and so on. The noise samples at 1.15MHz and 30MHz are distant 120 steps. The results are presented in Fig. 2. The significance of those correlations are shown in Fig. 3. As can be seen the p-values of most of them are below the 0.05 level of significance. That means that noise samples that are distant in the frequency are still correlated. Fig. 2 depicts that the correlation coefficient have a kind of periodicity with period about 25 steps (6.01MHz frequency distance). In every period the correlation increases until it reaches a peak value. Then the correlation decreases with the frequency until the end of the period and then it repeats this behavior. The peaks are observed at 20, 45, 70 and 95 steps. The peak values become smaller with the frequency increase. This is the first time that the periodic behavior of the correlation coefficients of the power line noise samples, in the frequency domain, is revealed. Undoubtedly, the noise samples at different frequencies are correlated and consequently are statistically dependent.

The statistical significance of the correlation coefficient of the noise samples measured in

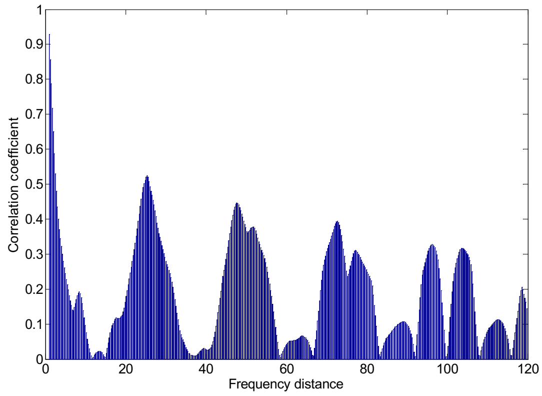

Fig. 2. Average correlation coefficient between noise samples that are 2 steps up to 120 steps distant.

different frequencies even being far away to each other is attributed to the fact that those noise samples are the frequency components of repeated phenomena in the time domain that have the same general characteristics impressed in the frequency domain. Those are the noise impulses that have certain statistics concerning time duration, amplitude and inter-arrival time. Those characteristics are measured in the time domain. However, the fourier transform could reveal the spectrum characteristics of the noise impulses.

Impulsive noise is more likely to be the reason for the statistically significant correlation among certain frequencies as it is found that is stronger and prevails the background noise. Any relationship that exists among background noise samples in the frequency domain could not be revealed when measurements are not made in the time domain where impulsive noise can be distinguished from background noise.

3 Pdf of the power line noise samples

In the section that follows the probability density functions of the noise density for every frequency where the measurements took place are extracted. The noise samples were processed and the normalized histogram of their amplitudes was extracted for every frequency in the frequency span of measurements. Using the smoothing splines method [10] the shape of the probability density functions is revealed. For instance, the normalized histograms and the corresponding smoothing spline curves are shown in Fig. 4 for the frequencies 1.15MHz, 1.81MHz, 12.03MHz and 12.63MHz.

The noise samples' magnitude before processing were transformed in dB. The shape of the curves looks like the probability density distribution of

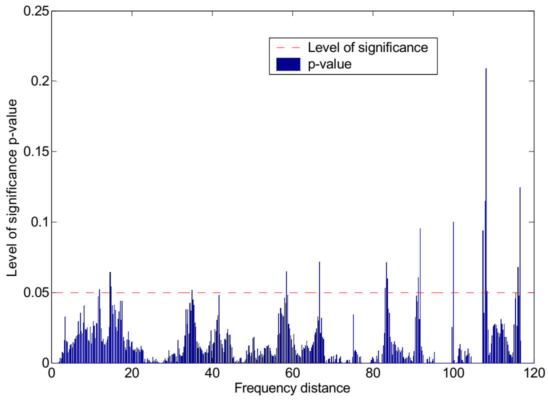

Fig. 3. Average level of significance of the correlation between noise samples that are 2 steps up to 120 steps distant.

Middleton's canonical class A noise as depicted in [11]. The model is described with equation (1).

$$f_I(I) = \sum_{m=0}^{\infty} \frac{A^m}{m!} e^{-A} \cdot 1/(\sigma_g^2 + m\frac{\sigma_I^2}{A}) \cdot e^{-(\sigma_g^2 + m\frac{\sigma_I^2}{A})^{-1} I} \quad (1)$$

Power line noise indeed can be described adequately by that curve. The left part of the probability density function (see Fig. 4) is in fact the noise component when m=0 (no noise impulses occurred) and as claimed in [11-12] it corresponds to the gaussian component of the noise. The right part of the probability density function stands for the impulsive component of the noise. The model for the Middleton's class A noise when the random variable is expressed in dB has some special properties that are quite helpful when a researcher tries to extract the noise probability density function using data obtained by measurements. The model involves three parameters that are adequate to express the p.d.f. Those are the σ_g^2, which is the mean power of the gaussian noise, the σ_I^2 which is the mean power of the impulsive noise and A that expresses the impulsive noise traffic. σ_g^2 and σ_I^2 are connected through equation 2.

$$\Gamma_A = \frac{\sigma_g^2}{\sigma_I^2} \quad (2)$$

Those three parameters necessary for equation 1 can be easily determined by a normalized histogram of the measured data. The mean power of the gaussian noise σ_g^2 is the point on x-axis that the left part of the p.d.f. has the peak. The height *h* of the left peak is connected with A with equation 3.

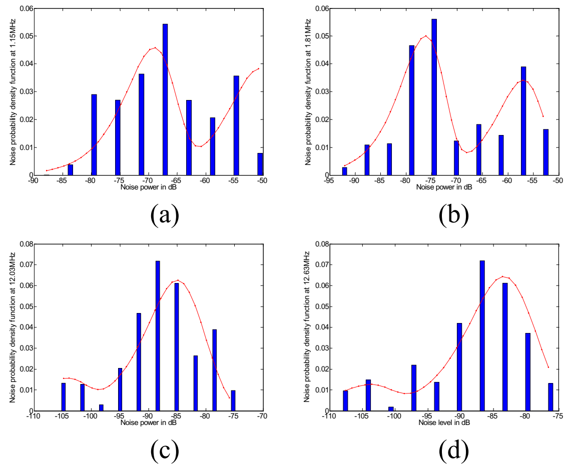

Fig. 4. Indicative normalized histograms of the noise power density at 4 different frequencies. The splines curve approximation is plotted to show the approximating p.d.f.'s shape.

$$A = \ln(0.0847/h) \quad (3)$$

Finally, the distance on x-axis between the left peak and the right peak is connected with Γ_A with equation 4.

$$\Gamma_A = [A(10^{(X_{RightPeak} - X_{LeftPeak})/10} - 1)]^{-1} \quad (4)$$

The proofs of equations (3) and (4) are included in [11].

The location on x-axis of the two peaks and the height of the left peak are prominent even when data measurements are rough. Therefore, the determination of the actual parameters of equation 1 is quite accurate. This is the main advantage of the described statistical extraction of the p.d.f.'s. In Table 1 the σ_g^2, Γ_A and A are presented for each measured frequency. Please note that in Table 1 the σ_g^2 has been transformed in dBm.

The exact weightiness of the σ_g^2 and σ_I^2 parameters is shown in fig. 1 where both of them are plotted simultaneously with all of the noise measurements. The lower dark line is σ_g^2 and the upper dark line is σ_I^2. Neither the one nor the other can be considered as average values of the noise power for every frequency. σ_I^2 does not fluctuate as much as σ_g^2 does. The explanation is simple. The frequencies where σ_g^2 exhibit notches are probably frequencies of radio stations (i.e. narrowband noise). As radio stations

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Table 1. PDF Parameters for 124 frequencies between 1.15MHz and 30 MHz.

FreqIn MHz	A	σ_g^2 in dBm	Γ_A	Freq In MHz	A	σ_g^2 in dBm	Γ_A	Freq In MHz	A	σ_g^2 in dBm	Γ_A	Freq In MHz	A	σ_g^2 in dBm	Γ_A
1.1509	0.6473	-39.177	0.0516	8.3632	0.7341	-56.588	0.2592	15.3351	0.0572	-59.456	6.3227	22.7877	1.4778	-75.879	0.0425
1.3914	1.1683	-40.745	0.0527	8.6036	0.7816	-60.456	0.0950	15.5755	1.4584	-80.227	0.0126	23.0281	1.4007	-76.143	0.0593
1.6318	1.0503	-43.406	0.0265	8.8440	0.7837	-60.215	0.0404	15.8159	1.6037	-80.259	0.0064	23.2686	1.5829	-79.183	0.0269
1.8121	0.5486	-46.266	0.0491	9.0844	0.8371	-60.971	0.0388	16.0563	1.2536	-79.992	0.0178	23.5090	1.5114	-76.168	0.0864
1.8722	0.5559	-45.953	0.0192	9.3248	0.8039	-60.529	0.0162	16.2967	1.3036	-79.929	0.0075	23.7494	1.4662	-76.553	0.0510
2.1126	0.8947	-47.183	0.0050	9.5653	0.7019	-64.187	0.0218	16.5371	0.0797	-65.686	1.8575	23.9898	1.7077	-80.886	0.0260
2.3530	1.0736	-46.379	0.0562	9.8057	0.6145	-64.890	0.0141	16.7775	0.4281	-61.426	0.2962	24.2302	2.3668	-73.348	0.0195
2.5934	1.0678	-48.663	0.0040	10.0461	0.4083	-62.518	0.0834	17.0179	0.2827	-61.426	0.2033	24.4706	0.7493	-63.804	0.2599
2.8338	0.8528	-48.475	0.0132	10.2865	0.5268	-62.066	0.0442	17.2583	1.3948	-81.059	0.0100	24.7110	1.9598	-81.090	0.0310
3.0742	0.7882	-48.387	0.0128	10.5269	0.5045	-62.474	0.0500	17.4987	1.5211	-81.718	0.0202	24.9514	1.5973	-76.676	0.0686
3.3146	0.9044	-55.559	0.0008	10.7673	0.4816	-59.883	0.0429	17.7392	1.6014	-80.855	0.0167	25.1918	1.6781	-81.404	0.0199
3.5550	0.7964	-55.245	0.0030	11.0077	1.7610	-74.063	0.0262	17.9796	1.6786	-74.772	0.0257	25.4322	1.6803	-80.808	0.0121
3.7954	0.7552	-55.487	0.0103	11.2481	1.5940	-70.891	0.0143	18.2200	1.4590	-75.086	0.0296	25.6726	1.7255	-80.463	0.0087
4.0358	0.8079	-56.161	0.0110	11.4885	0.1751	-54.186	1.7358	18.4604	1.4701	-80.525	0.0120	25.9131	0.8363	-54.549	0.1451
4.2763	0.9184	-58.815	0.0335	11.7289	0.3781	-58.032	0.3505	18.7008	1.3310	-75.882	0.0303	26.1535	0.2695	-51.073	0.4706
4.5167	0.9705	-54.273	0.1037	11.9693	0.2808	-57.517	0.5159	18.9412	1.3066	-76.773	0.0201	26.3939	1.8422	-80.431	0.0100
4.7571	0.9704	-55.189	0.0330	12.0294	1.8296	-74.863	0.0186	19.1816	1.3875	-77.363	0.0137	26.6343	1.2903	-76.409	0.0540
4.9975	0.9164	-56.407	0.0419	12.2097	1.8833	-71.221	0.0114	19.4220	1.3598	-80.369	0.0087	26.8747	1.3042	-80.933	0.0331
5.2379	0.7167	-58.063	0.0582	12.4502	1.9834	-75.506	0.0045	19.6624	1.3992	-80.290	0.0070	27.1151	1.2915	-80.792	0.0511
5.4783	0.7089	-59.004	0.0588	12.6305	2.0449	-74.458	0.0136	19.9028	1.3674	-80.055	0.0184	27.3555	1.2460	-81.122	0.0201
5.7187	0.6680	-61.078	0.0285	12.6906	2.0379	-74.502	0.0068	20.1432	1.3782	-79.929	0.0317	27.5959	1.1397	-78.875	0.0962
5.9591	0.8240	-61.222	0.0244	12.9310	1.9232	-74.859	0.0075	20.3836	1.3112	-76.152	0.0297	27.8363	1.0501	-79.007	0.0619
6.1995	0.9013	-60.346	0.0502	13.1714	1.9396	-77.294	0.0017	20.6241	1.1605	-75.707	0.0152	28.0767	1.1016	-78.875	0.0291
6.4399	0.9094	-65.639	0.0199	13.4118	1.8679	-77.576	0.0069	20.8645	1.2252	-77.451	0.0168	28.3171	1.1614	-78.699	0.0842
6.6803	0.9241	-65.398	0.0073	13.6522	1.7157	-77.545	0.0069	21.1049	1.4544	-78.166	0.0445	28.5575	1.2202	-77.000	0.0893
6.9208	1.0575	-61.627	0.0241	13.8926	1.9316	-77.278	0.0069	21.3453	1.4386	-77.407	0.0271	28.7980	0.9528	-78.556	0.0785
7.1612	0.9522	-65.586	0.0136	14.1330	1.9594	-77.357	0.0083	21.5857	1.3676	-78.160	0.0473	29.0384	0.9318	-78.825	0.0775
7.4016	1.0350	-65.200	0.0122	14.3734	1.6443	-78.361	0.0059	21.8261	1.4926	-77.633	0.0494	29.2788	0.8845	-78.781	0.0444
7.6420	0.9352	-51.182	0.6682	14.6138	1.4484	-78.376	0.0137	22.0665	1.5001	-75.446	0.0341	29.5192	0.8541	-78.825	0.0478
7.8824	0.9848	-60.610	0.0600	14.8542	1.9446	-69.244	0.0134	22.3069	1.4108	-75.663	0.0218	29.7596	0.8251	-78.380	0.0247
8.1228	0.8527	-60.183	0.0284	15.0947	1.3147	-62.235	0.2126	22.5473	1.4429	-75.180	0.0231	30	1.0051	-79.914	0.0168

have almost constant transmission power their power is added to the background noise level of the power lines because the model cannot distinguish it from the underlying background noise as the latter varies by time in terms of hours just like the power originating from the radio stations. This fact has as consequence the model to be slightly misled and the impulsive noise level to be stronger than it is actually at the frequencies where radio stations transmit. From Fig. 1 it is evident that at the frequencies where σ_g^2 has great notches, the impulsive noise σ_I^2 also seems to be reinforced. The reader can easily see from equation (2) that for certain Γ_A when σ_g^2 is increased, σ_I^2 is also increased.

Finally, the greater the A parameter the more frequent the impulsive noise is. Hence, from Table 1 we can distinguish the frequencies that impulsive noise prefers and hits more frequently. Frequencies greater than 11MHz suffers from greater impulsive noise traffic.

4 Validity Limits of the Power Line Channel Noise Models

In this section some comments are made about the validity limits of the power line channel models. It was observed that the strong and almost constant radio station's emission affects negatively the operation of the models. As already mentioned in section 3 regarding these strong power emissions as constituents of the gaussian component of the power line noise, the impulsive noise power is depicted stronger than it is actually. This was observed when we plotted together the histogram of the noise samples (actual p.d.f.) with the p.d.f. originated from Middleton's formula. Although, the left part of the p.d.f. matched well, the right part could not fit perfectly, even when 100 members of the summation of equation 1 was used. Those frequencies present greater R.M.S.E. (root mean square error) between the smoothing splines curve approximating the actual p.d.f. and the curve from equation 1, compared to the R.M.S.E. in frequencies where there were no radio stations transmissions.

On the other hand, due to the significant correlation that the noise samples have, we can extract noise models for frequencies that are not included in Table 1 by means of interpolation. Obviously, the more narrow the frequency step of the noise measurements is, the more accurate interpolation can be.

The Middleton's canonical formula for class A noise was constructed to describe noise phenomena in the time domain in the first place. In this paper it was used in the frequency domain as it was found, after statistical analysis of the data measured in the frequency domain, that equation 1 can describe sufficiently the p.d.f. of the noise spectral density for every measured frequency. The p.d.f.'s parameters extraction is the major contribution of this study.

5 Conclusions and Further Research

In this paper a power-line channel noise model is proposed. It is based entirely on measurements in the frequency domain since OFDM, is a prominent candidate for power line communications. The model is in fact a family of parallel models in the frequencies of interest. The frequency distance between two models is 240.4KHz. We used thousands of spectrum analyzer sweeps in the frequency range of interest. The family of the noise models must be enhanced with new members. This can be achieved shortening the frequency distance and perform a new campaign of measurements. The narrower the frequency distance is, the more accurate the power line model can be. The enhanced p.d.f.'s family will be attained shortly. Additionally, the dependency of the A, s_g, s_i, from the frequency is a next step in our research.

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