Analyses and Modeling Impulse Noise Generated by Household Appliances

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Abstract. *This paper describes analysis of impulse noise generated by small household appliances. Furthermore we propose a new model of impulse noise based on the averaged power spectrum and the random phase generation with various phase distributions. The Gaussian, Weibull and Log-normal phase distributions were used to generate random phase. As a result of this approach, new impulses appear – they are different in the time domain but in the frequency domain new impulses have the desired power spectrum and the randomly generated phase.*

Keywords

Fourier transformation, Gaussian, Henkel–Kessler model, impulse noise, log-normal, probability density, Weibull.

1. Introduction

The digital subscriber lines (xDSL) technology is one of the most widely used technology for the Internet connection and the multimedia services to the household appliances in the Czech Republic. One of the most common DSL technology was Asymmetric Digital Subscriber Lines (ADSL2+) [4] which has been already replaced by Very-High Speed Digital Subscriber Lines (VDSL2) [5]. All the transmitted services are named as "Triple play" which is composed of Voice over IP (VoIP), Data and IPTV (TV over IP protocol).

The xDSL systems are carried on a metallic loop. Services transmitted in xDSL systems are influenced by different kinds of disturbances. The most common disturbance is mutual interference of signals from neighboring pairs within one cable – so-called far-end crosstalk (FEXT) and near-end crosstalk (NEXT). Other disturbances are the Radio-frequency interference (RFI), background noise and impulse noise. All of these types of disturbances have a negative impact on the quality of transmitted services. Especially IPTV and VoIP are very sensitive to the impulse noise, more in [11]. Therefore the aim of this paper is to analyse and model the impulse noise generated by household appliances.

2. Impulse Noise

Impulse noise is a specific noise which can originate in the electromagnetic radiation of power cables, power switching and control, and other installations and devices. Impulse noise has typical random amplitude with peak voltage and random arrival time.

Previously, there have been done several measurements and analyses by various telecommunication operators such as the British Telecom, France Telecom and others. It was proved that impulse noise is a random process and consequently PSD (power spectral density) is possible to make as a probability of estimations of so-called pseudo PSD [2].

2.1. Impulse Noise in Standardization

Special impulses are mentioned in the recommendation ITU-T G.996.1. There is described a method to testing DSL against to impulse noise. This method uses so called impulse No. 1 and No. 2 with specific amplitude (u_e) in milivolts at which impulses causes an error of estimated probability that a second will be errored [1].

2.2. Group of Electrical Impulse Noise

The group of electrical impulse noise consists of the REIN (Repetitive Electrical Impulse Noise), SHINE

(Single High Impulse Noise Event) and PEIN (Prolonged Electrical Impulse Noise) (e.g. [2], [3]).

- REIN is a typical repeating noise with a short length less than 1 ms and with constant frequency period (100 or 120 Hz) [2].
- SHINE is an impulse noise lasting more than 10 ms.
- PEIN is the disturbing signal composed of non-repeating interference pulses.

Table 1 compares all types of groups of electrical impulse noise.

Tab. 1: Comparison of groups of electrical impulse noise [3].

Noise type	Typical Burst length	Repetitive	Desired modem behavior
REIN	<1 ms	Yes	No bit errors
PEIN	1–10 ms	No	No bit errors
SHINE	>10 ms	No	No sync loss

2.3. Experimental Modeling of Impulse Noise

The measurements of impulse noise were carried out in networks of the Deutsche Telekom, British Telecom, KPN Netherland and others on the metallic line in the past time. The approach to the impulse noise by the Deutsche Telekom was based on a generator realizing the impulse-voltage density, see more in (e.g. [6], [7], [8], [9] and [10]). This is known as the:

$$f_i(u) = \frac{1}{240u_0} \cdot e^{-\left|\frac{u}{u_0}\right|^{\frac{1}{5}}}, \qquad (1)$$

where u_0 is a parameter indicating the shape function.

The length density in the form of one or two log-normal densities

$$\begin{aligned} f_l(t) &= B\frac{1}{\sqrt{2\pi s_1 t}} \cdot e^{-\frac{1}{2s_1^2}ln^2\frac{t}{t_1}} + \\ &+ (1-B)\frac{1}{\sqrt{2\pi s_2 t}} \cdot e^{-\frac{1}{2s_2^2}ln^2\frac{t}{t_2}}, \end{aligned} \qquad (2)$$

where B is a parameter indicating xTU-R or xTU-C and t_1, t_2 are the median values and s_1, s_2 are the shape parameters of the lognormal densities.

The inter-arrival time density

$$f(t) = \lambda e^{-\lambda t}, \qquad (3)$$

where λ is the average rate of arrivals.

3. Study of Impulses Noise by the Appliances

In our experimental measurement, we haven't observed the impulse noise on a real metallic line as the companies mentioned earlier but we have focused on the impulse noise from household appliances. The household appliances were connected to the power supply where a power supply cable was tightened in parallel with the telephone line of two meters length. The near-end of telephone line was terminated with an impedance terminator and the far-end of telephone line was terminated with a so called balun (balance-unbalance transformer). Signals from both the power cable and the telephone line were observed by the digital oscilloscope, more in (e.g. [11], [12]). The measuring workplace was proposed similarly according to the recommendation in ITU-T G.996.1 [1].

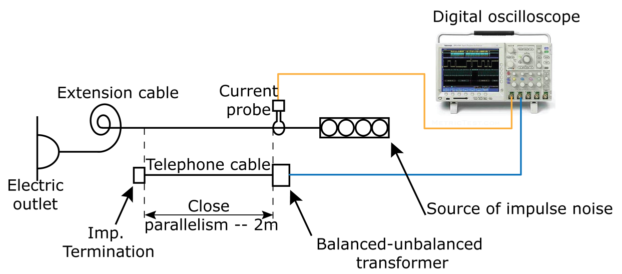

Fig. 1: Measuring workplace [12].

Devices used in this research: Drill (EXTOL), Blender (SOFTmix ETA), Battery charger (HAMA), Display, Fan, Dryer. In this paper, we only worked with results from the Drill, Blender and Dryer.

The time records of noise from household appliances have been recorded by a digital oscilloscope. The sample frequency was 50 MHz and the number of samples in the record was 10^7 of samples. The noise has been measured in different statuses as: e.g. startup, plugged in, shutoff, running, regulation and operation.

Figure 2 shows a record from running Blender in the time domain. Also Fig. 3 shows a record from running Drill and Fig. 4 shows a record from running Dryer. All records contain 200 ms of noise stream.

Each recorded noise has been studied from the viewpoint of the amplitude probability density, arrival time probability density and length of impulses.

3.1. Analysis of Amplitude of Impulse Noise

We focused on the analysis of probability density of amplitude in this subchapter. The modified exponential probability density has been selected as an approx-

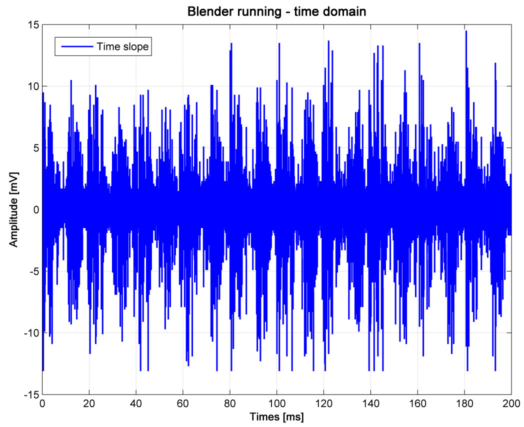

Fig. 2: Illustration of Blender running – time domain.

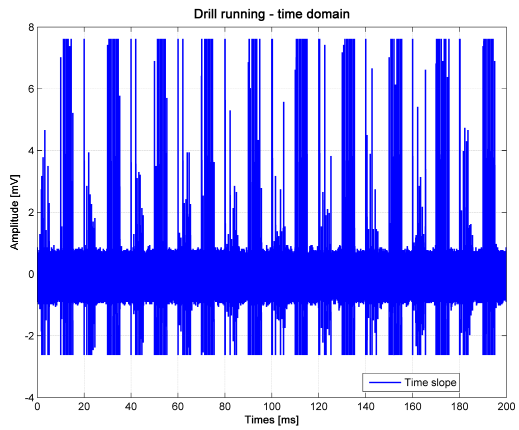

Fig. 3: Illustration of Drill running – time domain.

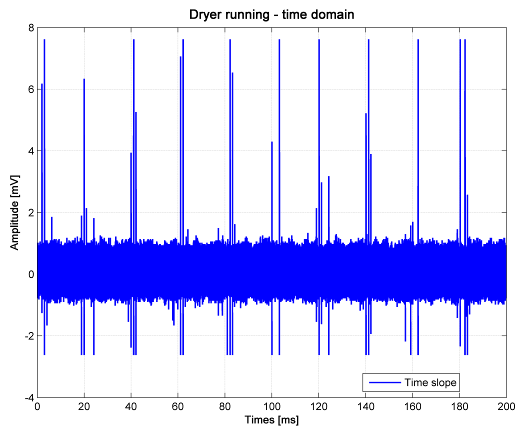

Fig. 4: Illustration of Dryer running – time domain.

imate model. The Henkel–Kessler model was selected as a reference model. The exponential probability density function (pdf) of amplitude is:

$$pdf_{ampl} = \lambda e^{-\lambda|u|}, \quad (4)$$

where $|u|$ is a parameter of amplitude, λ is the reciprocal value of the mean amplitude.

The algorithm we proposed was created in the Matlab program and analyses the amplitude from noise record and compares the exponential probability density of amplitude with the Henkel-Kessler model (HK model).

We can see that the HK model tends to the probability from the histogram for the appropriate parameter u0 in Fig. 5, Fig. 6 and Fig. 7. The appropriate parameter u_0 is shown in the legend.

Figure 5 shows the histogram and probability density of amplitude for Drill running. Figure 6 shows the histogram and probability density of amplitude for Blender running. Figure 5 shows the histogram and probability density of amplitude for Dryer running.

In the end, in this subchapter we can note that the HK model is a better approximation of amplitude probability density but our results of the proposed model show that the model can be used for approximately the the exponential probability density as well.

3.2. Analyses of Inter-arrival Time of Impulse Noise

This subchapter deals with the analysis of inter-arrival time. The HK model uses the exponential probability density for the inter-arrival time.

During analyses of the inter-arrival time for the selected household appliances it has been observed that some groups of impulses occurred with the approximately same cycle.

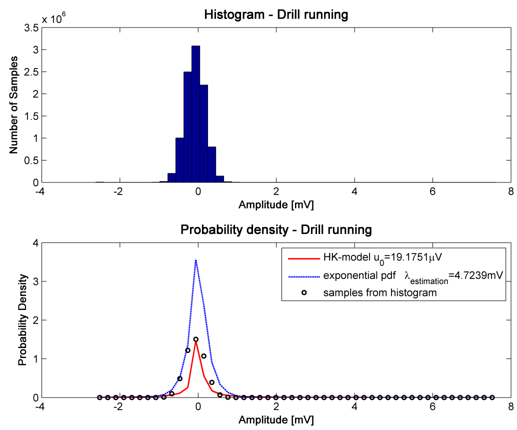

Fig. 5: Histogram and probability density of amplitude – Drill running.

This is the deterministic behaviour and the behaviour of impulses is typically the same as the REIN noise. The inter-arrival time between the impulses in

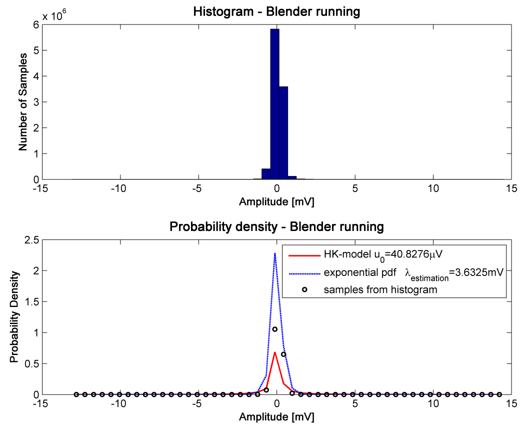

Fig. 6: Histogram and probability density of amplitude – Blender running.

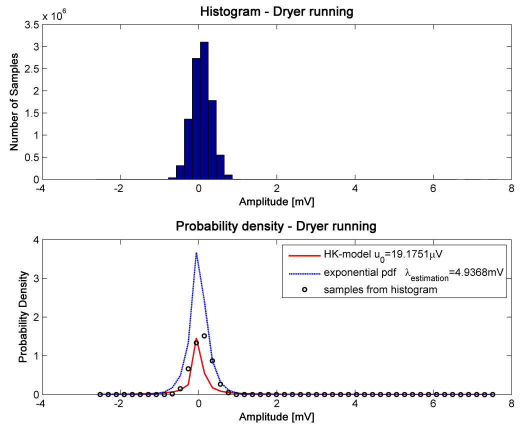

Fig. 7: Histogram and probability density of amplitude – Dryerr running.

the group is approximately the same or variety. Variety of the inter-arrival time tends to the approximation of the Poisson process with the cumulative function of exponential distribution.

The Drill has the mean inter-arrival time between groups of impulses τ_{iag} = 9.95 ms and the mean inter-arrival time between impulses in groups τ_{iaing} = 0.67 ms. The impulses have the typically behaviour like the REIN on the basis of τ_{iag} and the deterministic behaviour on the basis of τ_{iaing}. Figure 8 shows the inter-arrival of impulses.

The Blender has τ_{iag} = 10.86 ms and τ_{iaing} = 0.17 ms. The impulses have the typically behaviour as the REIN noise on the basis of τ_{iag} and the exponential distribution on the basis of τ_{iaing}.

The Dryer has similar a behaviour as the Drill; τ_{iag} = 18.21 ms and τ_{iaing} = 1.47 ms. The impulses have the typically behaviour as the REIN noise on the basis of τ_{iag} (the frequency period is 55 Hz) and the deterministic behaviour on the basis of τ_{iaing}.

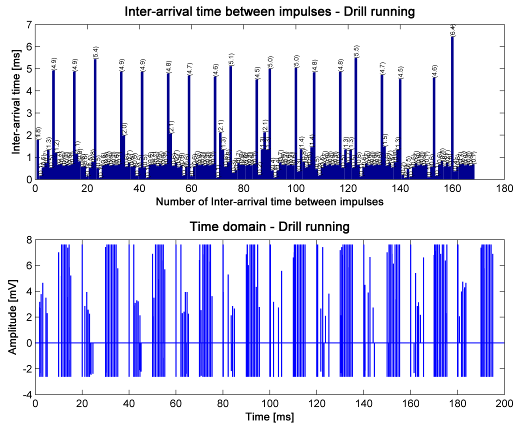

Fig. 8: Inter-arrival time between impulses – Drill running.

The conclusion of this subchapter is that the inter-arrival time can have the deterministic behavior as the REIN noise or the exponential distribution which is used in the HK model.

4. Modeling of New Impulse Noise

In our experiment, we approached a model of impulse noise as follows: each recorded noise from household appliances has been studied separately. The model of impulse noise was divided into several steps:

- Firstly, we found impulses with the similar power spectrum.
- Then, we found out the averaged power spectrum from impulses of the first point.
- Next, we randomly modeled phase with various probability density.
- Next, by the help of IFFT (Inverse fast Fourier transform) we got time impulses.
- Finally, we compared the old average power spectrum (from the second point) with the average power spectrum obtained by the new time impulses.

It has been observed that the best of time length of impulse is N = 512 samples (i.e. 10.24 μs) in all records. The histogram length of impulse is shown in Fig. 9.

Estimation of the power spectrum has been calculated by Matlab from this formula:

$$C_{(s)}(n\omega_0) \approx T_{Sa}\frac{1}{N}|DTF\{s_N[k]\}|^2 = \frac{T_{Sa}}{N}|DTF\{s_N T_{Sa}[kT_{Sa}]\}|^2, \quad (5)$$

$$\Omega_0 = \frac{2\pi}{N} = \omega_0 T_{Sa} \Rightarrow \omega_0 \frac{2\pi}{T_{Sa}} \frac{1}{N} = \frac{\omega_{Sa}}{N}, \quad (6)$$

where T_{Sa} is a sampling time, N is the number of samples from signal in the time domain, k is one of the samples, ω_0 is distance between samples in the spectrum and the DFT is the Discrete Fourier Transform. The matrix $\mathbf{C}$ presents the power spectral matrix type $N \times b$ where N represents 512 samples and b is the number of found impulses shown as column vectors.

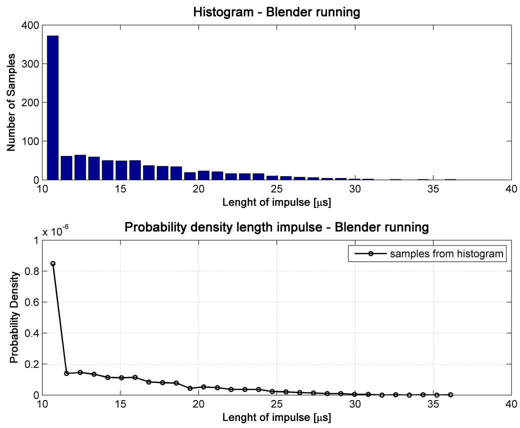

Fig. 9: Histogram and probability density length of impulse.

$$\mathbf{C} = \begin{pmatrix} c_{1,1} & c_{1,2} & \cdots, & c_{1,b} \\ c_{2,1} & c_{2,2} & \cdots, & c_{2,b} \\ \vdots & \vdots & \cdots, & \vdots \\ c_{N,1} & c_{N,2} & \cdots, & c_{N,b} \end{pmatrix}, \quad (7)$$

where row $r \in \{1, 2, ..., N\}$ and column $s \in \{1, 2, ..., b\}$. The following technique has been used for location of similar impulses with the power spectrum. The extent dissimilarities in the power spectrum between two vectors are described in:

$$d_{i,j} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (C_i(n) - C_j(n))^2}, \quad (8)$$

where i and j are indexes of vectors, C is the power spectrum and N is the number of samples. The matrix $\mathbf{D}$ is a type of matrix $b \times b$. This matrix contains the extent dissimilarities in the power spectral every by every column vectors, then $d_{i,j} = 0$ for $i = j$.

$$\mathbf{D}_{(b,b)} = \begin{pmatrix} d_{1,1} & d_{1,2} & \cdots, & d_{1,j} \\ d_{2,1} & d_{2,2} & \cdots, & d_{2,j} \\ \vdots & \vdots & \cdots, & \vdots \\ d_{i,1} & d_{i,2} & \cdots, & d_{i,j} \end{pmatrix}, \quad (9)$$

where row $i \in \{1, 2, ..., b\}$ and the column $j \in \{1, 2, ..., b\}$. The vector $\mathbf{M}_{min}$ contains a minimal value from each column from the matrix $\mathbf{D}$. The matrix $\mathbf{M}$ is a type of matrix $b \times b$ and contains the vector $\mathbf{M}_{min}$ for each row.

$$\mathbf{M}_{min} = (min\{d_{*1}\} \cdots, min\{d_{*b}\}), \quad (10)$$

$$\mathbf{M} = \begin{pmatrix} \mathbf{M}_{min,1} \\ \vdots \\ \mathbf{M}_{min,b} \end{pmatrix}. \quad (11)$$

The matrix $\mathbf{W}$ is a type of matrix $b \times b$ and equals to the subtraction the matrix $\mathbf{D}$ and the matrix $\mathbf{M}$.

$$\mathbf{W} = \mathbf{D} - \mathbf{M}. \quad (12)$$

The column vector $\mathbf{B}_{*j}$ is a vector which contains indexes of impulse with the similar power spectrum. The column vector $\mathbf{B}_{*j}$ is calculated in the Matlab program with the use of the function *find*. The function *find* finds out indexes from the column vector $\mathbf{W}_{*j}$ which are less than the maximal value in the column vector $\mathbf{D}_{*j}$ multiple by the parameter α. The parameter α ($\alpha = 0.1 = \frac{10\ \%}{100}$) is a value in percentage from the maximum of the column vector $\mathbf{D}_{*j}$.

$$\mathbf{B}_{*j} = find(\mathbf{W}_{*j} < max\{\mathbf{D}_{*j}\}\alpha). \quad (13)$$

The matrix $\mathbf{Q}$ is a type of matrix $b \times b$ and contains indexes from impulses with the similar power spectrum.

$$\mathbf{Q} = (\mathbf{B}_{*j}, \cdots, \mathbf{B}_{*b}). \quad (14)$$

The averaged power spectrum from the impulses with the similar power spectrum can be computed with the following formula:

$$C_{avg,N}(\omega) = \frac{1}{k} \sum_{i=1}^{k} C_{N,i}(\omega), \quad (15)$$

where $C_{N,i}$ is the column vector of the power spectrum from matrix $\mathbf{C}$, k contains indexes of the column vector obtained by the column vector $\mathbf{Q}_{*j}$. These indexes correspond to the column indexes in the matrix $\mathbf{C}$.

4.1. Generate Random Phase

Above it has been dealt with the average power spectral from impulse. If we want to create an impulse in the time domain with the average power spectrum we have to generate the random phase and then use the inverse Fourier transform. The impulses in the time domain have been transformed by the Fourier transformation.

$$S(\omega) = \int_{-\infty}^{\infty} s(t) e^{-j\omega t} dt, \quad (16)$$

where *s(t)* is a signal in the time domain, $S(\omega)$ is Fourier transform signal *s(t)*.

$$S(\omega) = |S(\omega)| e^{j\Phi(\omega)}, \quad (17)$$

where $|S(\omega)|$ is an estimate of amplitude spectrum and $\Phi(\omega)$ is a phase function.

In our case, the phase function $\Phi(\omega)$ has been generated randomly with the relevant probability density. It has been used these probability densities – Weibull, Log-norm and Gaussian.

Figure 10, Fig. 13 and Fig. 17 show the power spectral density obtained from the time impulses with the similar power spectrum – gray line represents the average power spectral density (PSD) – black line is used for the appropriate household appliance. The sample frequency was F_s = 50 MHz and the impedance was Z_C = 50 Ω. The average power spectral density has been used to generate impulses with this power spectrum and random phase.

The PSDs in the Fig. 10 and Fig. 13 contain the peaks on the relevant frequencies. These peaks could cause the error in seconds as well as the block errors. This will affect adversely the quality of services for example the IPTV service. The current common VDSL modems are able to distinguish the white noise with PSD -140 dBm/Hz. The PSD in the Fig. 19 contains some peaks in bandwidth 5–10 MHz.

1) Drill

It was modeled 802 impulses with the random phase in this case, the Weibull distribution phase and the same of the average power spectrum from Fig. 10. Figure 11 shows a comparison of the required PSD (red line) and PSD from the modeled 802 impulses (blue line). It is visible that the PSD from the modeled impulses tends to the required PSD. Figure 12 shows one of the 802 modeled time impulses where the phase has the Weibull distribution.

2) Blender

There were modeled 803 impulses with random phase, the Gaussian distribution phase and the same of the average power spectrum from Fig. 13. The Figure 14 shows a comparison of the required PSD (red line) and PSD from the modeled 803 impulses (blue line). There is visible that the PSD from modeled impulses tends to the required PSD. The Figure 15 and Figure 16 show the modeled impulse in the time domain where the first one has the distribution phase – Gaussian and the second one has the distribution phase – Log-normal.

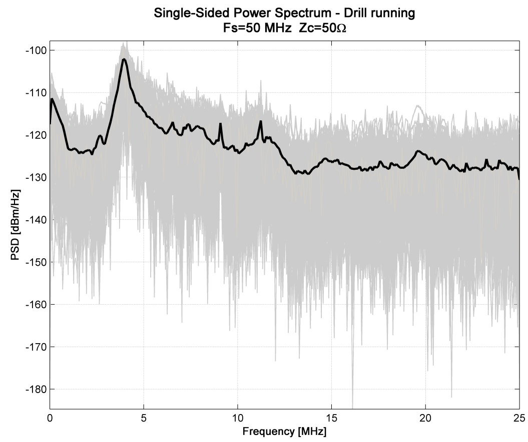

Fig. 10: Similar PSD obtained from 802 time impulses in Fig. 3 (Drill running).

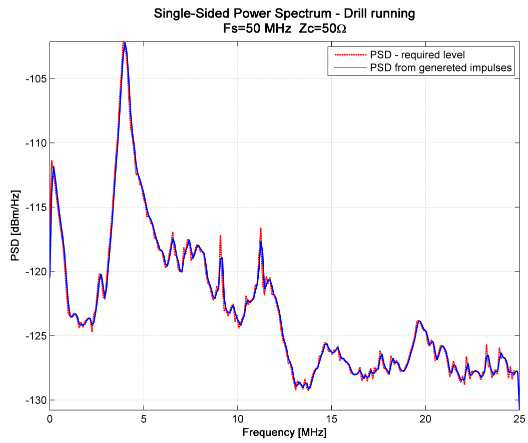

Fig. 11: The required PSD (red line) and PSD from modeled 802 impulses (Drill running).

3) Dryer

In this case it was modeled only 26 impulses with random phase; the Weibull distribution phase and the same of the average power spectrum from Fig. 17. Figure 18 shows a comparison of the required PSD (red line) and PSD from the modeled 26 impulses (blue line). It is visible that the PSD from the modeled impulses tends to the required PSD.

The conclusion of this subchapter is that it is possible to model the impulses with the similar power spectrum with the random density phase. The random den-

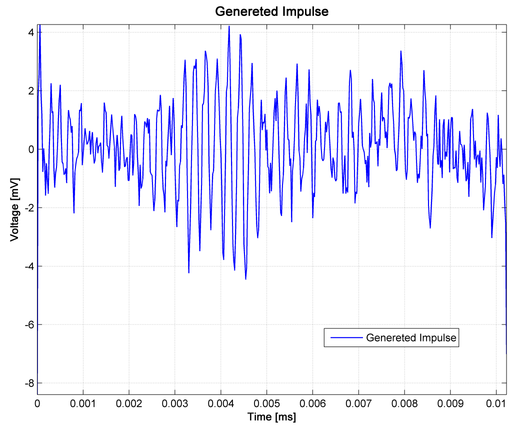

Fig. 12: Example one of the modeled time impulse with distribution phase – Weibull (Drill running).

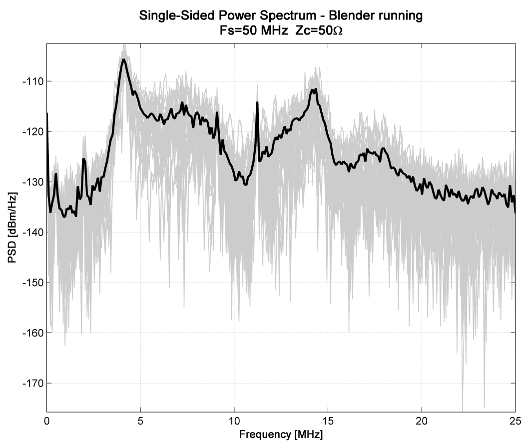

Fig. 13: Similar PSD obtained from 803 time impulses in Fig. 2 (Blender running).

Fig. 14: The required PSD (red line) and PSD from modeled 803 impulses (Blender running).

sity phase changes shape of the impulse in the time domain but the power spectrum tends to the required shape.

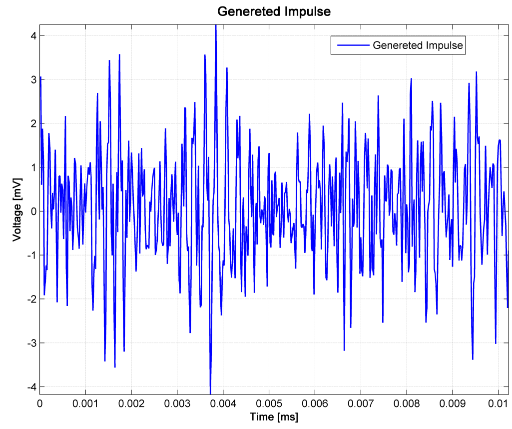

Fig. 15: Example one of the modeled time impulse with distribution phase – Gaussian (Blender running).

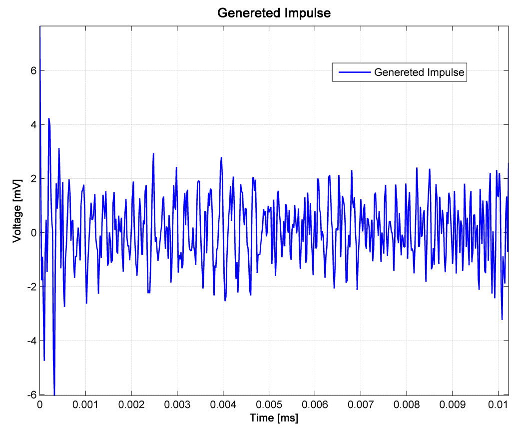

Fig. 16: Example one of the modeled time impulse with distribution phase – Log-normal (Blender running).

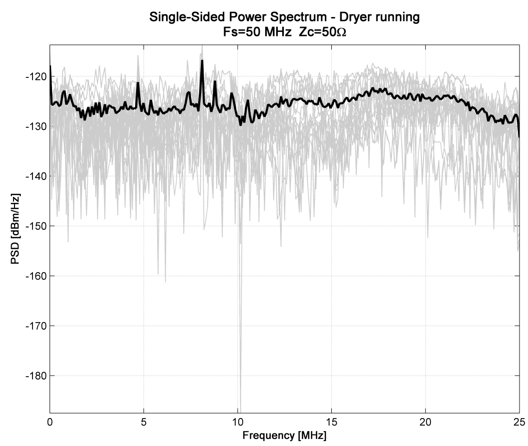

Fig. 17: Similar PSD obtained from 26 time impulses in Fig. 4 (Dryer running).

Fig. 18: The required PSD (red line) and PSD from modeled 26 impulses.

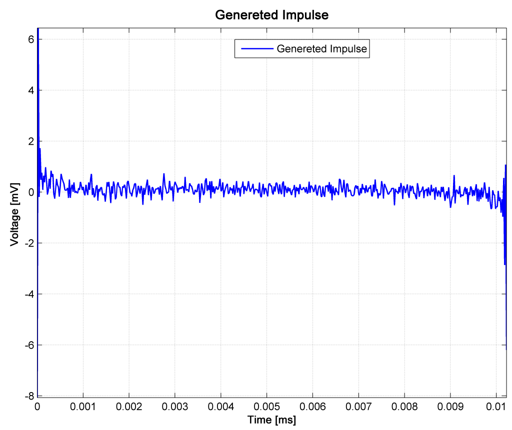

Fig. 19: Example one of the modeled time impulse with distribution phase – Weibull (Dryer running).

4.2. White Gaussian Noise

This subchapter deals with the modeling of the white Gaussian noise. A noise which is located between the impulses has been analysed e.g. in Fig. 3 or Fig. 4.

The white Gaussian noise has a PSD constant over the simulation bandwidth $|f| < \frac{f_s}{2}$. The variance is, by definition, the area under the power spectrum, more in [13].

$$\sigma^2 = \frac{1}{2} N_0 f_{Sa}, \tag{18}$$

where N_0 is the random number (noise) generator variance, f_{Sa} is the sampling frequency.

Figure 20 represents the histogram of noise and the probability density of amplitude. It seems that the noise between the impulses tends to the white Gaussian noise. The PSD of noise is illustrated in Fig. 21; we can see some groups of peaks which can cause the block errors. Nevertheless it is possible to approximate this noise by the white Gaussian noise as shown in Fig. 22.

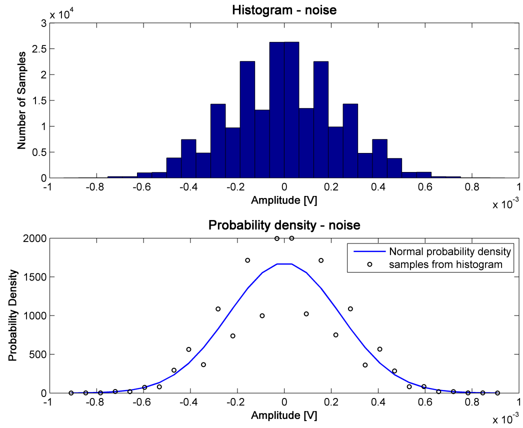

Fig. 20: Histogram and probability density of amplitude –noise.

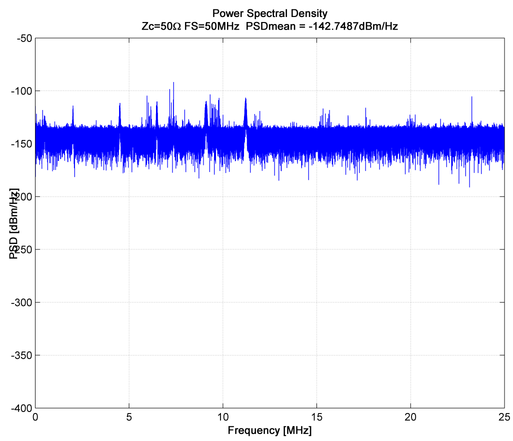

Fig. 21: Power spectral density – noise located between impulses e.g. at Fig. 4.

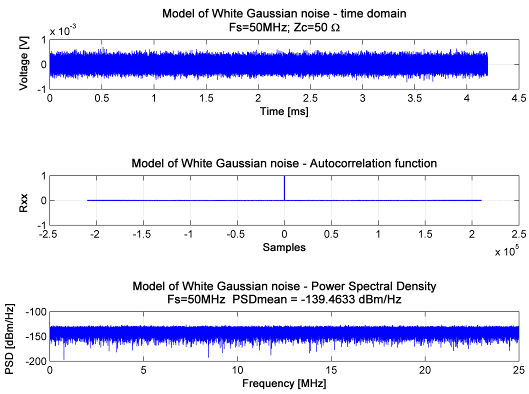

Fig. 22: Power spectral density – Model of White Gaussian noise.

5. Conclusion

Impulse noise negatively affects services provided on xDSL technology for example IPTV or VoIP. Therefore it is important to analyse this type of disturbance. Analyses of impulse noise in the telephone line were described in a model made by Mr. Henkel and Mr. Kessler [6], [7].

We mainly focused on impulse noise generated from the household appliances in our research. The home appliances are the most common source of interference penetrating into the telephone line in households. We obtained a conception of PSD of these impulses through the analysis of these impulses. We could obtain impulse noise models of household appliances using modeling of the new impulses. These models can be appropriate for correctness preserving configuration of xDSL (ADSL2+ and VDSL2) telephone lines against impulse noise.

Regarding our results shown in this paper, the probability density is very approximate to the HK model. The inter-arrival time seems to have deterministic behavior as the REIN noise or the exponential distribution which is used in the HK model.

Our modeling of impulse noise is based on the averaged power spectrum obtained from impulses with approximately similar power spectrum. The appropriate phase distribution in the frequency domain is created using random phase. New impulses were made with IFFT. New impulses had averaged power spectrum and random modeled phase. Furthermore new modeled impulses showed different shape in the time domain but the PSD was approximately the same. As we mentioned above, for this study we used the distribution phase with Gaussian, Weibull and Log-normal distribution. For the further research beta, exponential and uniform distribution will be tested. Noise between impulses tends to the best approximation by the use of the white Gaussian noise.

Practical application of this research can be used for the appropriate parameter settings for xDSL connections protection against impulsive interference. Impulse noise effects can be suppressed by the use of suitable combination of Reed-Solomon code and interleaving parameter e.g. [5] or [14] and newly retransmission (RTX) also known as ARQ (Automatic Repeat-reQuest) [14], but on the contrary, the maximum achievable transmission speed is reduced.

Acknowledgment

This paper has originated thanks to grant support obtained from the Technology Agency of the Czech Republic within the project TA03011192 “Research and Development of Next-generation Devices for Communication over High-voltage Power Lines”.

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