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Synchronization of the Communication with Wide-Band Impulse Modulation over Power Line Channels

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I. Introduction

The continuing tendency of using some natural or intended for other purposes environments for communication, as the free space, the water environment, or the power line, imply new requirements towards the realization of reliable communication.

The parameters of these environments – media for communication, unlike the specially designed transmitting electrical or optical media, are not constant, they are variable in time and, in many cases even in the time interval of one symbol. The changes, usually random, can be regarded in many cases as short-term stationary processes. This concerns the transfer function, presented by its frequency characteristic or the impulse reaction and the interferences as well. Some noises, that are different in their nature, spectral composition and probability parameters, are distributed over the power line. The methods of communication over such environments must apply some averaged indicators which remain relatively constant. The multi-path propagation is typical for these environments, which leads to dispersion of the signals transmitted, long impulse reaction and this is expressed in the frequency domain as considerable unevenness with deep flops, sometimes exceeding 40 dB. The dynamics of the alteration of the different media and the conditions can be altered in wide boundaries. It can be co-measurable with the rate of the symbols received in communication with moving objects. The alterations in the power line are slow, they can occur after tens of minutes, but they are very deep [1, 2].

In order to compensate this variability of the media, different tools are used. The most direct methods are connected with the multiple transmission in the frequency, time and space domain, keeping one and the same type of division. More efficient, but more complex are the convolution encoding and the use of error-correcting codes, or the simultaneous use of the two methods. The interleaving together with the error-correcting codes is a very efficient technique which compensates the variability of the communication channel. Like in conventional encoding the quick alterations are efficiently suppressed in it by the participation of the transfer function with its mathematical expectation, the impulse and coloured noises being transformed into white Gaussian noise.

For media with slow changes of the communication parameters, the conventional encoding and the interleaving influence basically the disturbances, transforming them into white Gaussian noise. For a power line especially, which has a distinctly expressed cycle-stationary noise component, with a period, equal to the network semi-cycle, these techniques allow the efficient increase of the communication reliability.

For variable media a successful type of modulation proves to be the multi-frequency one, combined with error-correcting encoding. In its essence it approximates the real transfer function of the channel by Hear's functions. Each sub-channel has a uniform transfer function and potentially each sub-channel may be information loaded variously, depending on the noises in it. The implementation in OFDM is particularly efficient. In this type of modulation all the sub-channels have an equal band.

The conventional approach towards providing orthogonality (interferences absence) among the different information flows is to provide each flow with its separate physical media in space division, a separate frequency band in frequency division, a separate time interval in time division or the combination of the two.

In code division (CD) the orthogonality is achieved using complex signals, with a frequency band, much wider than the capacity of the information symbols being received. The separate information flows in a system with CD are simultaneously transmitted, separately one from another, in one and the same frequency band. Each flow is provided with its own signal, signature, orthogonal to the remaining ones. The signatures may be assigned properties of self-orthogonality – the auto-correlation function of each signature contains periodical zeroes, their period coinciding with the duration of the symbols transmitted. This allows time interleaving of the symbols transmitted without the appearance of inter-symbol interference. This CDMA allows prolonging of the transmission time by expansion of the frequency band along the two axes (time and frequency) practically independently.

The code division possesses some interesting properties, which make it very appropriate for communication over variable media.

- The frequency expansion reduces the sensibility towards frequency-selective fading and frequency concentrated interferences. At sufficiently large expansion the connection reliability is defined by the averaged frequency parameters.
- The time expansion makes the communication dependent on some average-statistic parameters.

- It allows the design of communication systems with common access not implying any operating constraints – synchronous or asynchronous.
- The total power is not larger than the summed one at frequency division.
- At much smaller number of the flows (the users) than the frequency expansion, CDMA system can work in one and the same frequency band with narrow-band systems without any significant mutual influence. This allows the design of systems with episodic communication without a license for the frequency domain.

The influence of the communication flows for every channel is accepted as inter-channel interference. It diminishes for inactive participants and vice versa. This allows the design of the system for a larger number of the flows. In systems providing a resource – frequency or time, its real use is incomplete, very often below 50 %. In CDMA the flow increase leads to noises increase.

These features of CDMA make it very appropriate for communication over a power line. For average-statistic communications (up to several kbps) which use wide-band impulse modulation, due to the low spectral density, the narrow-band systems can operate together without any mutual influence and without the necessity for a license.

The paper presented investigates the signals in CDMA with broad-band impulse modulation, the influence of the impulse reaction of the power line and the achieving of synchronization between the transmitter and the receiver.

The expansion enables the transformation of the varying channel into a channel with white additive noise.

The expansion is a simple linear operation, much simpler than encoding, interleaving and decoding.

II. System model

The communication over a power line is considered, of the type of direct expansion, code division, common access (DS-CDMA) using signals with small spectral density, which can work together with other narrow-band communications without any considerable inter-system interferences. Such a system may be used without any license. All the users are equal in rights and each one can transmit to any other or to an arbitrary part of the users under the condition that only one transmitter is turned on. As an exception it is sometimes possible several users to transmit simultaneously. The constraint is not a system one, but due to the accepted limit on the sub-noise spectral density of the signals transmitted. The discipline of switching to transmission is not considered. It is possible to use a version of CSMA/CA (carrier sense multiple access with collision avoidance), but for the simplified system considered, a more simplified approach can be accepted, moreover that the constraint for one transmitter working is not too strict.

The internal clock is synchronized with the network frequency. This enables considerable simplification of the system for synchronization. The alteration of the network cycle is too slow. The measurements show that for the rather long interval (in comparison with the transmission rate) of 10 min, the alteration of the network period does not exceed 10 μs, a time, co-measurable with the duration of the symbols transmitted.

The information is transmitted by a series of short-term impulses – mono impulses with time position and amplitude, which form the signature of each user. It is a sequence of equally positioned mono impulses with one and the same inverse phase or zero and a frequency, divisible to the transmission speed of the information symbols. In the general case there are not any constraints on its duration, but in real systems it is limited to several information symbols. The increase of the duration increases the resistance against impulse interferences.

The signature for *j*-th user is:

(1) $$\varphi_j(t) = \sum_{l=0}^{l-1} \sum_{k=0}^{k-1} g\left(t - a_{kl}.k\frac{T}{K} - lT\right),$$

where $g(t)$ is the mono impulse, T is the duration of one information symbol, K – the number of the time positions in the interval T, in which the mono impulse $g(t)$ can be transmitted, l – the duration of the signature, measured by the number of the periods T. In the present paper we assume, that the larger part of the coefficients a_{kl} are zeroes, in order to satisfy the requirement for sub-noise communication. In order to avoid the inter-symbol interference, the intervals with a duration T of the signatures in one and the same channel must be mutually orthogonal. A protection interval is introduced between the separate symbols, passive, with a duration larger than this of the maximal impulse reaction. In order to keep the regularity in the representation, this interval is introduced with null initial values of the coefficients a_{kl} for values of k, close to K.

The duration of the impulse reaction $\tau_{\rm pl}$ of the network depends on its configuration. Some measurements for building houses estimate it as 0.5 μs [4].

The signature is presented by the vector

(2) $$a_j = \left| a_{j00} a_{j10} \dots a_{jk+1,0} a_{j01} a_{j11} \dots a_{jk-1,L-1} \right|^{\rm T}$$

or in a more convenient record by the matrix

(3) $$A_j = \begin{vmatrix} a_{j00} a_{j01} \dots a_{j0L-1} \\ a_{j10} a_{j11} \dots a_{j1L-1} \\ \dots \\ a_{jk-1,0} a_{jk-1,1} \dots a_{j,k-1,L-1} \end{vmatrix}.$$

All the vectors (columns) in matrix A_j must be orthogonal in order to avoid the inter-symbol interference. The separate vectors are the values of a discrete signal, segmented in equal intervals, each one with a duration K. The orthogonality may be expressed by the scalar product

(4) $$< A_{jk}, A_{jf} >= \delta(k - l),$$

where A_{ij} is the *i*-th vector matrix for *j*-th signature.

The condition for orthogonality can be presented in the more general form:

(5) $$A_j(k) A_j^{\rm T}(l) = \delta(l - m) I,$$

where A_j (k) is the matrix A_j with all its vectors shifted k times to the left or to the right, and l is a singular matrix.

Each user is provided with his own signature, orthogonal to the remaining ones in the communication system.

(6) $$A_l A_m^{\mathrm{T}} = \delta(l-m) I \, .$$

The orthogonality condition of all the signatures, participating in the communication is

(7) $$< a_i, a_j >= \delta(i-j)$$

In the anti-phase modulation accepted, the signal transmitted is as follows:

(8) $$S(t) = \sum_i b_i \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} g\left(t - a_{kl} . k \frac{T}{K} - lT - iT \right).$$

Here $b_i = \pm 1$, and i is the consecutive binary information symbol.

According to (5), the channel signal being transmitted can be regarded as a result of the convolution of the binary symbols b_i with a signature φ_i (t).

The transmitter can be functionally presented as composed of a k divisible quantizer of the incoming binary symbols b_i, which stimulates the filter (2) and has an impulse function $\varphi_i(t)$ (Fig. 1).

$$S(t) = \sum_i b_i \varphi_j (t - it)$$

The signal at the input is

(9) $$r(t) = s(t) * h(t) + n(t) \, ,$$

where $h(t)$ is the line impulse reaction and $n(t)$ are the noises, presented as additive, entering directly the receiver input and * is the convolution symbol.

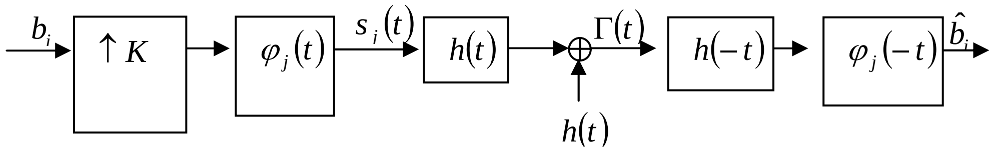

Fig. 1

If Gaussian nature of the noise is assumed, the optimal reception is reduced to de-convolution of the signal received with respect to the impulse reaction of the line and the signature, as shown on Fig. 1.

III. Model of the channel

The power line as a communication channel is significantly, but comparatively slowly altering in comparison to the transmission rate. In a multi-users system the impulse reaction or the transfer function respectively, is very different for every two communicating users. Its determination is a significant function of the reception.

One quite frequently used model of the Power Line (PL) for wide-band signals [2, 3], borrowed from RF propagation is:

$$h(t) = \sum_i L_i \delta(t - \tau_i)\,. \tag{10}$$

This model approximates rather well the real process of RF at point reflectors. It is equivalent to a set of all-pass filters with different time delay and attenuation. The signal received is a geometrical sum of the separate replicas of the signal transmitted. Such a model is quite far from the real processes in PL. The attenuation increases with the increase of the frequency, and the reflections of the non-homogenities are still more dependent on the frequency in module and in phase as well [5, 6]. The received reflected wide-band signals in their form remind very slightly of the transmitted ones [4]. The replicas are with a poorer content of the high-frequency components. Despite the features mentioned, this model is often used thanks to its simplicity. With its help in [3] some quite relevant estimates of the probabilities for error reception are obtained. This model can be regarded as decomposition of a not complete and not orthogonal system of functions.

IV. Mono-impulses

The present paper discusses communication using wide-band signals with small spectral density and distributed over a channel with unknown and significantly variable impulse reaction. The energy of such signals is determined by the averaged transfer function of the channel, as well as by the averaged noise power. Similar signals are particularly appropriate for communication over a power line, where besides the variation in time, the transmission is very different between each two users as well.

The most often used form of the mono impulses [3, 8] is the second derivative of the Gaussian function:

$$s(t) = \frac{1}{\sqrt{2\pi}}(1 - \frac{t^2}{T_0^2})\exp(-\frac{t^2}{2T_0^2})\,.$$

The time dependence and the spectral characteristic are shown in Fig. 2 (for T_0 =1 with the continuous line and for T_0 =2 with the dash line). This mono-impulse covers a wide frequency band and it does not contain a dc component, has no side leaves and its density is greater at lower frequencies, where the attenuation over the power line is smaller. The derivatives of the Gaussian function of a higher order have a similar spectral form [8].

Fig. 3 shows the time form and the spectral density of another signal that may be used as a mono cycle. It has the advantage that its generation is simple and it does not contain a dc component. The right side in its spectrum can be easily suppressed by a simple analog low frequency filter. With an appropriate selected first zero in the spectrum, the suppression of the side leave can be realized by the power line itself, without any additional filters.

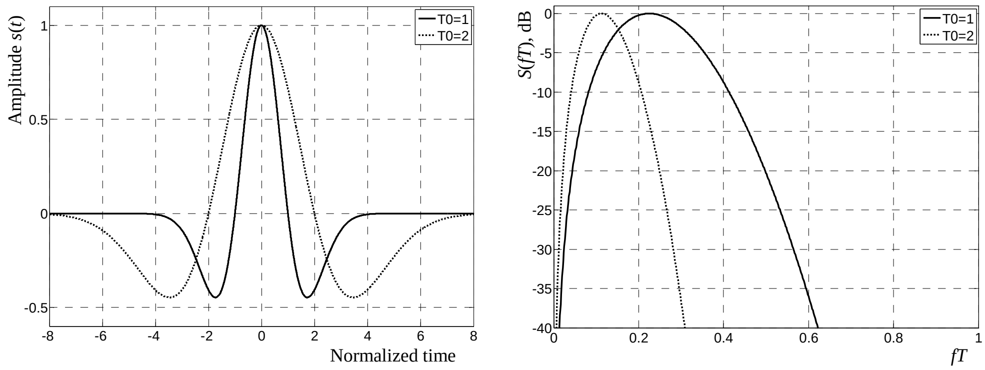

Fig. 2. $s_2(t) \Leftrightarrow S_2(fT)$, $T_0 = 1$ and $T_0 = 2$

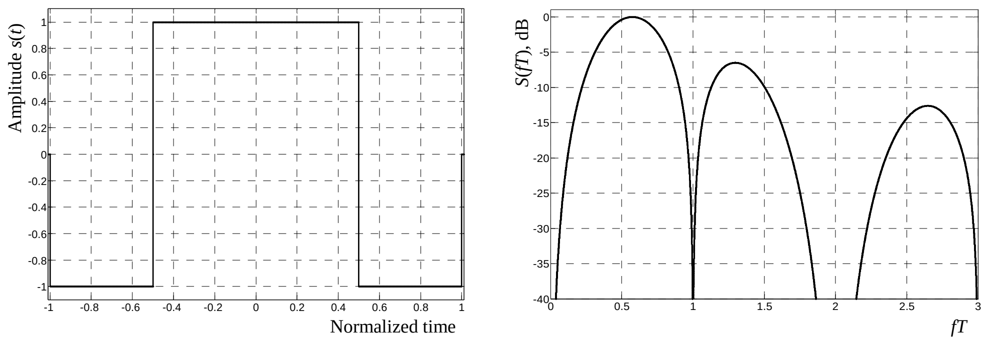

Fig. 3. Fourier transform pair $s_1(t) \Leftrightarrow S_1(fT)$

The signal $s(t) = (\frac{t}{T_0})^8 e^{-2\pi(\frac{t}{\alpha T_0})^2}$ has a wider auto-correlation function. This feature is very useful for the mono impulses, since it does not imply very strict requirements towards the synchronization. Its time and spectral form are shown on Fig. 4.

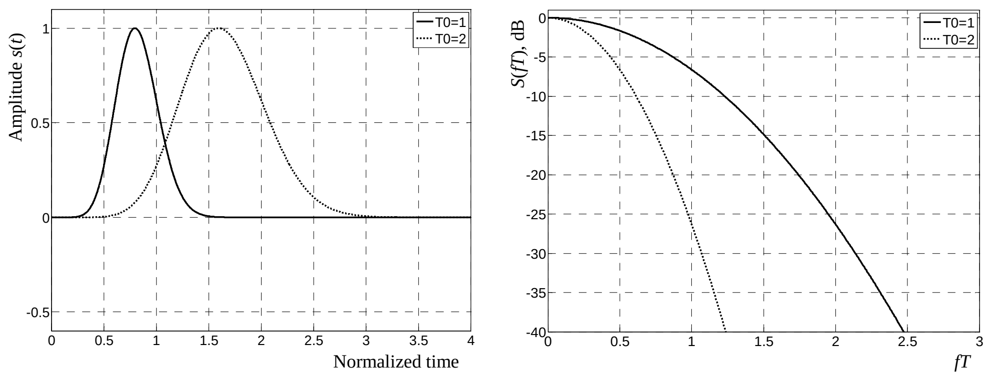

Fig. 4. $s_3(t) \Leftrightarrow S_3(fT)$, $T_0 = 1$ and $T_0 = 2$

For the communication along a power line we can use as a mono impulse also the initially generated rectangular impulse and the transmission of an appropriate spectral characteristic by a chain, added to the line. The spectrum of such an impulse is described by the sinc*x* function, which contains a low-frequency domain and a constant component and slowly attenuating leaves after the first zero. The suppression of the low frequency domain is achieved naturally with the selection of the low limit frequency of the coupling transformer. The side leaves are considerably limited by the natural capacity of the line. An additional constraint can be introduced by the coupling chain, necessary for the diminishment of the electro-magnetic emission. As far as no precautions are possible, the power line acts like a reception-transmission antenna. Very inefficient, in fact, but for frequencies above 10 MHz this emission can get unfeasibly large values.

When choosing sufficiently narrow rectangular impulses, for example, within the limits of 10-50 ns, the signals, coming to the receiver input, are close to the impulse reaction of the line. Fig. 5 shows the transmitted mono impulse with a base width of 25 ns and the signal received at a certain point in the real network, located at 40 m.

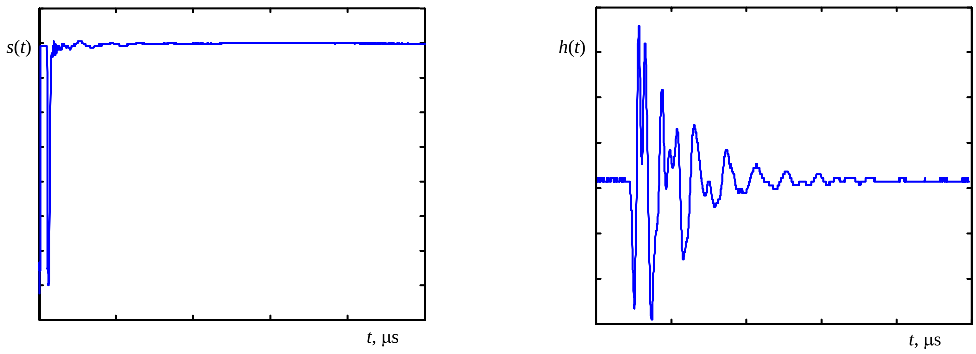

Fig. 5. Impulse response of a real network

V. Synchronization and estimation of the channel impulse reaction

One not very complex communication system is examined herein with an average transmission rate up to 200 kbit/s. The reception is coordinated (correlation respectively). The mono impulses used are near to rectangular ones in shape, with a first zero of the spectral characteristic above the feasible domain of the line, above 30 MHz. The signals received are close to the channel IR for such mono impulses. We assume that the timing of all the users is coordinated with the power voltage. This permits the search for mono impulses in a limited time domain during the initial synchronization, and in more complicated communications the accounting of the dependence of the impulse reaction on the phase of the power voltage.

We assume that the coordination is accomplished with the reaction of the channel to the mono impulses. The coordination with the mono impulse used requires higher frequency of quantization and a following convolution with IR.

For a simplified system of communication it is appropriate to define directly the reaction to the mono-impulse $\tilde{g}(t) = g(t) * h(t)$, where $h(t)$ is IR of the channel, using a pilot signal. A series of N_p can be used as a pilot signal, that represent not modulated mono impulses with an interval, coordinated with the accepted rate of transmission, in each case larger than the duration of the channel IR. Synchronous accumulation is realized in the receiver. The signal obtained after the end of the pilot series is the reaction of the channel in form and in phase to the mono impulse.

The reaction, shown in Fig. 5 is typical with respect to the residual noise after 50-divisible accumulation in a PL with different loads – computers, printers, a photo-copying apparatus, luminescent illumination, oscilloscopes, an air-conditioning system. The attenuation of the signal received is 54 dB.

VI. Conclusion

An approach is suggested for the design of a multi-user communication system over a power line with the usage of wide-band mono impulses, a signature, obtained by position modulation and anti-phase modulation of the information symbols. A part of the voltage which determines the channel reaction is experimentally studied in a real line and it has shown high operating reliability. The reception of the information flow is a subject of another publication.

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Синхронизация коммуникации при помощи широкополосной импульсной модуляции по электрической линии

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(Р е з ю м е)

В работе предлагается подход для построения коммуникационной системы по электрической линии с использованием сигналов с малой спектральной плотностью. Система способна работать совместно с узкополосными системами без заметной взаимной интерференции. Показаны экспериментальные результаты некоторых элементов системы