I. INTRODUCTION

Power line carrier (PLC) communications is an area of research that has been studied for many years, although it has never reached the mainstream of communications research activities. Commercial systems have been difficult to implement and simple in capability. More recent research has focused on solving many of the problems facing PLC communications using the latest communications technologies, with new high-speed devices soon to reach the market. This section of the thesis gives an overview of current PLC systems and standards, details the challenges limiting the capacity of current systems, and explores the modern communications methods applicable to PLC methods. Focus is given to low voltage (<1kV) PLC technologies. That is, those that are applicable for domestic home network use.

PLC communications is a well-known and reasonably common method of communication in domestic households. In fact, it is high-speed PLC opens up new field for telecommunication services without additional cabling. The conditions for the high-speed data transmission in the low voltage power distribution network are unfavorable due to frequency selective properties, varying impedance, considerable noise, high attenuation and other effects.

Characteristics of PLC channel make it extremely difficult to achieve a high-speed transmission with the conventional single-carrier approach, which requires a complex adaptive equalization to compensate for the strong frequency selective behavior of the power lines.

II. NOISE AND DISTURBANCE

Common causes of noise on electrical power networks include corona discharge, lightning, power factor correction banks and circuit breaker operation. On the low voltage network, much of this noise is filtered by medium/low voltage transformers, so the most common interference in low voltage domestic networks can be attributed to the various household devices and office equipment connected to the network. Noise and disturbances on the electrical power network can be generally classified as follows: [1]

(i) Waveshape disturbances
These include:
- a. Over-voltages, both persistent (>2 seconds) or surges (<2 seconds).
- b. Under-voltages, both persistent or surges.
- c. Outages.
- d. Frequency variations.

(ii) Superimposed disturbances
These include:
- a. Persistent oscillations, either coherent or random.
- b. Transient disturbances, both impulse and damped oscillations. Waveshape disturbances are usually of little effect on PLC systems. Transceivers are usually robust enough to cope with minor over-voltage and under-voltage disturbances. Naturally, in the case of (i)(c), total line outages will make information transmission impossible. Yet the outage of a piece of distant equipment will not affect the performance of a domestic PLC system. Harmonic disturbances can be a major source of disturbance, yet these occur at frequencies below those designated for PLC communications by statutory authorities. Frequency variations can cause major problems in PLC systems, as many simple systems rely on the mains carrier (50Hz sine wave) for synchronisation between transmitter and receiver. Frequency variation in this wave will cause transmission error. Modern systems overcome this obstacle by avoiding reliance on the mains carrier for synchronisation. On the medium voltage network, class (ii) noise is attributed to large factories with extensive plant or machinery, and industrial users with poorly filtered appliances. On the low voltage network, a number of household appliances are most often responsible for superimposed disturbances.

Vines et al [3] further categorise type (ii) noise as:
- A. Noise having line components synchronous with the power system frequency;
- B. Noise with a smooth spectrum;
- C. Single event impulse noise, and;
- D. Non synchronous noise.

A. Noise having line components synchronous with power system frequency.

The usual source of this noise (hereafter called Type A noise) are triacs or silicon controlled rectifiers (SCR’s), found domestically, for example, in light dimmers or photocopierson. The spectrum of this noise consists of a series of harmonics of the mains frequency (50Hz). There are three ways to combat this kind of noise: [1]

- As the frequency spectrum of class A noise is regular, successful communication may be possible with modulation schemes that avoid, or have nulls, at these frequencies.
- Filter these noise components out using accurate notch filtering. So far a qualitative description of noise on the low voltage network has been given. With an understanding of the noise inherent on domestic power networks, various suggestions can be made for the development of a PLC communications system:
- Appropriate error correcting codes should be implemented to cope with noise types A, B and C.
• To avoid type D noise, television line frequency and harmonics should be avoided when modulating the signal onto the channel—no signal information should be transmitted at these frequencies.
• Some kind of frequency diversity (for example frequency hopping) should be implemented to cope with interference at unknown frequencies.

III. POWER LINE COMMUNICATIONS AND OFDM

The orthogonal frequency division multiplexing (OFDM) transmission divides the available broadband into many carriers each one being modulated by a low-speed data stream, promises to be a suitable modulation technique for high capacity power line communications (PLC). OFDM data transmission is a promising modulation technique that eliminates a need for complex equalizer. The basic idea behind OFDM transmission scheme is to divide the available channel bandwidth into a number of subchannels, each one being nearly ideal. A low-speed data stream modulates each subcarrier using QAM (Quadrature Amplitude Modulation) as subchannel modulation. The long symbol interval used in OFDM produces a much greater immunity to impulse noise and fast fades. The division of the available channel bandwidth into relatively narrow subbands provides a transmission rate close to capacity. It is intuitively reasonable that the overall bit rate is maximized if a power division among the subcarriers and a selection of the number of bits per symbol (modulation level) for each subcarrier are chosen so that the bit error rates in all the subchannels are equal. The lower modulation level is assigned to lower SNR subchannel, whereas higher modulation level is assigned to high SNR subchannel. Optimum modulation level and power allocation per subcarriers in an adaptive OFDM system, according to channel conditions, provides the potential for a higher transmission rate. Channel state estimation is required for equalization, impulse response shortening of the effective channel and adaptive modulation level and power allocation in OFDM systems. The increasing demand for high-date-rate communications through the time-variant and frequency selective channel, as the power-line, makes blind channel identification very interesting since it does not require the transmission of a training sequence.

The mitigation of the time-dispersive characteristic of frequency selective channel is achieved by inserting a cyclic prefix between OFDM blocks (symbols), as a guard interval, the length of which is longer then length of the channel impulse response in order to avoid inter-OFDM symbol interference. OFDM with cyclic prefix results in negligible both intersymbol (ISI) and interchannel (ICI) interference and eliminates a need for complex equalizer. The insertion of the cyclic prefix to the OFDM signal induces its wide sense cyclostationarity that can be used for blind channel identification in OFDM systems [5]. The advances in digital signal processing are achieved by processing signals as cyclostationary [6, 7]. Cyclostationary signal processing techniques exploit the underlying signal periodicities. It exhibits as correlation between shifted spectral components. Exploitation of this inherent spectral redundancy associated with spectral correlation offers significant advantages at performing different signal processing tasks in difficult environments, as it is PLC. The spectral correlation density (SCD) evaluation and cyclic features analysis (spectral correlation characterization) are often a key stages to derive a proper signal processing of the cyclostationary signals.

OFDM signal with cyclic prefix is cyclostationary. The OFDM signal \(x(t)\) is a composite of \(N\) multiplexed QAM signals and can be expressed as:

\[
x(t) = R \left[ w(t) \cdot e^{j2\pi f_c t} \right]
\]

where \(f_c\) is the carrier frequency and \(w(t)\) is the complex envelope of \(N\) multiplexed QAM signals. The complex envelope of the OFDM signal with cyclic prefix has the form:

\[
w(t) = \sum_{k=0}^{N-1} y_{n,k} \cdot e^{j(2\pi f_c t + \gamma_{n,k})} \cdot q(t - kT)
\]

where \(\gamma_{n,k}\) is independent and identically distributed (i.i.d.) information symbol sequence (generally complex), \(N\) is the number of subcarriers, \(q(t)\) is a rectangular shaping pulse of duration \(T\) and \(T_s\) is the source OFDM symbol period. The complete OFDM symbol duration with guard interval \(T_g\) is \(T = T_s + T_g\). The cyclic prefix insertion destroys orthogonality of multiplexed QAM signals.

Conventional OFDM uses fixed subchannel modulation. However, in adaptive OFDM \(i\)th subchannel QAM, each with the same symbol rate \(f_c = 1/T_s\), can have a different modulation level \(M_i = 2^m\). The total number of transmitted bits per OFDM symbol is constant:

\[
L = \sum_{i=1}^{N} m_i
\]

The inverse DFT/DFT (Discrete Fourier Transform) is employed for the efficient baseband OFDM modulation/demodulation process and then \(T_s / N\) is sampling interval.

The complex valued information symbol sequence \(\{\gamma_{n,k}\}\) takes \(M\) values, i.e.:

\[
\gamma_{n,k} \in \{e^{j \theta_m}\}_{m=1}^{M}
\]

where in-phase components, \(a_{c,m}=R_e\{c_m\}\), and quadrature components, \(b_{c,m}=I_m\{\gamma_{n,k}\}\), of \(M\)-ary complex symbols \((a_{c,m}, b_{c,m})\) are arranged in a \(\sqrt{M} \times \sqrt{M}\) rectangular signal constellation. Mutual cos-sin dependence of the in-phase and quadrature components of \(M\)-ary PSK signals results in their circular signal constellation, i.e.:

\[
\gamma_{n,k} \in \{e^{j \theta_m}\}_{m=1}^{M} \Rightarrow \{e^{j(2m-1)\pi / M}\}_{m=1}^{M}
\]
Thus, M-ary PSK signal is constant-envelope QAM signal and that modulation with differential encoding reduces problem of equalization due to time-dispersive characteristic of a frequency selective channel.

A. Spectral correlation of OFDM signal

Spectral correlation of the complex envelope $w(t)$ of OFDM signal has the form [8]:

$$S_w^w(f) = \begin{cases} \sum_{n=0}^{\infty} Q(f - \frac{n}{T}, f - \frac{n}{T}) \cdot Q'(f - \frac{n}{T}, f - \frac{n}{T}), \alpha = \frac{1}{T} \\ 0, \quad \alpha \neq \frac{1}{T} \end{cases} \quad (6)$$

Following the procedure as in [6-8], the spectral correlation of OFDM signal $x(t)$, given by (1, 2), can be obtained in the form:

$$S_w^x(f) = \frac{q(t)}{\pi} \sum_{n=-\infty}^{\infty} Q(f - \frac{n}{T}, f - \frac{n}{T}) \cdot Q'(f - \frac{n}{T}, f - \frac{n}{T}) + Q(f - \frac{n}{T}, f - \frac{n}{T}) \cdot Q'(f - \frac{n}{T}, f - \frac{n}{T}), \alpha = \frac{1}{T} \quad (7)$$

where

$$Q(f) = \frac{\sin(\pi f T)}{\pi f} \quad (8)$$

is Fourier transform of rectangular shaping pulse $q(t)$. In view of eqn (7), OFDM signal with cyclic prefix exhibits spectral correlation at cycle frequencies equal to symbol rate $c/n/T$. In the case when there is no cyclic prefix it can be seen that orthogonality of the subcarriers on the complete symbol interval ($T=T_s$) destroys discrete-time cyclostationarity of OFDM signal [8].

Some results of the continuous-time cyclostationarity analysis of OFDM signal are presented in Fig.1 and Fig.2.

The spectral correlation magnitude for the complex envelope of OFDM signal (M=15) with cyclic prefix ($T=1.25 \cdot T_s$) is shown in Fig.1 and without cyclic prefix ($T=T_s$) in Fig.2. On these figures one can notice the above mentioned characteristic cyclic features of OFDM signals.

IV. CONCLUSION

This article covered PLC techniques, current devices and applications, as well as technical issues such as the challenges faced by PLC communications, an exploration of modern communications strategies suited to improving the performance of PLC systems. Exact analytical expression for the OFDM spectral correlation function is derived applying the proposed method, the characteristic cyclic features according to the cyclic prefix presence are analyzed and some computed and graphed results are presented.

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Abstract: Power lines and their associated networks are not designed for communications use. They are a hostile environment that makes the accurate propagation of communication signals difficult. Noise levels are often excessive, and cable attenuation at the frequencies of interest is often very large. Important channel parameters such as impedance and attenuation are time varying in unpredictable ways. This article covered PLC techniques. Technical issues such as the challenges faced by PLC communications, an exploration of modern communications strategies suited to improving the performance of PLC systems, and considerations unique to PLC systems have been addressed.

Exact analytical expression for the spectral correlation function of OFDM signal with cyclic prefix is derived applying the proposed method and some computed and graphed results are presented.

Abstract: U radu je ukazano na probleme prenosa digitalnih signala distributivnim energetskim vodovima niskog napona u okviru stambenih zgrada. Predložen je metod i izveden je tacan analiticki izraz za funkciju spektralne korelacije OFDM signale, na osnovu koje bi se odredjivala spektralna karakteristika, kao osnova za adaptivni prenos podataka vecim brzinama.

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