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Introduction to Robust, Reliable, and High-Speed Power-Line Communication Systems

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SUMMARY Power-line communication (PLC) systems have been assumed as the systems of low speed and low reliability. The low qualities of the systems, however, are not inherent of PLC but the result of inadequate design strategy of the systems. The systems with proper considerations of the characteristics of power-line as a communication medium achieve reliable high-speed data transmission in power-lines. In fact, the activities on the standardization of high-speed PLC systems have recently started in many countries, and variety of high-speed PLC systems are being to be purchased off-the-shelf. Following this trend of PLC, this manuscript first describes the features of power-line for communications and then explains technical issues on the design of PLC systems of the next generations as the infrastructure of information-communication technology age.

key words: power-line communications (PLC), high-speed, cyclo-stationary channel, OFDM, CDMA

1. Introduction

Power-line communications (PLC) make it possible to use ubiquitous electricity power-lines for the medium of communications. In a house, already installed power-lines and outlets behave as data-networks and ports. Since many data equipments and electric appliances are already connected to outlets, there is no necessity to introduce tangled cables for data communications. Not like wireless radio/infra-red LAN, terminals can have stable connection with PLC, even if they are divided by radio-shielding wall.

In addition to the advantage for in-house network, the application of PLC to access network also has attractive features. In general, the last one-mile to subscribers, or the local loop, is the most expensive part in public communication systems. The exploitation of low-voltage grid for communications may allow partial exemption from this cost.

Because of the attractiveness mentioned above, PLC is taking attentions especially in Europe and North America. In the last three years, about twenty in-house and access trials have been performed in more than ten European countries [1]. These trials include the pilot experiment in Essen, Germany, where 200 households and offices are connected to Internet with high speed (several Mbps) PLC. As a part of European Union research activities, The Fifth Framework Programme includes the project for PLC, i.e., "PALAS-Powerline as an Alternative Local Access (IST-1999-11379) [2]." The objective of the project is to develop a framework for the fast development and the market-orientated implementation of the PLC technology for high-speed access networks. In addition, in 1999, ETSI (the European Telecommunications Standards Institute) has also started a project, "ETSI Project Powerline Telecommunications (EP PLT)" to develop standards and specifications to provide telecommunication services via the existing public and private mains power networks. In addition, The PLCforum has been established on March 2000 in Switzerland with the aim of uniting and representing the interests of players engaged in PLC with 51 founding members out of 17 countries in 3 continents [3]. Also in the North America, the industry alliance named HomePlug has been established on March 2000, aiming to provide a forum for the creation of open specifications for high speed home power-line networking products and services [4].

Since power-lines are not designed for communication, there is no guaranty on the performance from the viewpoint of signal transmission. Thus PLC may encounter peculiar features of the power-line channel, such as inferior and unstable transmission characteristics, very low and time-varying impedance of lines, and strong man-made noise. In addition to these difficult challenges, the assigned bandwidth of PLC has been narrow (10–450 kHz in Japan, and lower than 150 kHz in Europe). Because of these difficulties, contrary to the recent recognition, PLC have long been disregarded as the systems with low speed and low quality.

The low speed and quality of the systems are not an ineluctable destiny of PLC. The assigned bandwidth for PLC is much wider compared with those for mobile communication systems and telephone modems. The maximum power allowed to emit is also high, compared with mobile telephone terminals. Also impulsive noise and single tone jamming are easier to suppress than Gaussian noise of the same power. These facts imply that PLC has high potential to achieve much higher speed and quality.

It is the reason of the insufficient performance of the former PLC systems that they simply introduced the signaling schemes developed for the environment completely different from power-lines. Moreover, the

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systems defined in regulatory are even old-fashioned without the technologies used in modern telephone modems and mobile systems. Conversely, the employment of the sophisticated schemes may realize much higher performance than conventional PLC systems. For example, in [5] Matsumoto concludes that the PLC system with the date rate about 5 Mbps is possible for the frequency band of 10–450 kHz.

Following the backgrounds introduced above, this manuscript first reviews the basic concepts on PLC and then describes the characteristics of power-lines as communication media such as a simple model of non-stationary power-line noise. Then the discussion on the technical issues for the realization of new generation PLC succeeds, and concluding remarks are drawn.

2. Classification of PLC

2.1 Narrow-Band and Wide-Band

According to the Japanese regulations, unlicensed PLC should use frequency in the range of 10–450 kHz. In Europe, the limitation is more strict because of broadcasting on the long waves, and the frequency range regulated by European Committee for Electrotechnical Standardization (CENELEC) is 3–148.5 kHz. In this manuscript, PLC in these low-frequency ranges is named as *Narrow-Band PLC.*

Recently, many countries, including Japan, have begun to consider the deregulation of the frequency band for PLC, up to about 30 MHz. For example, ETSI has defined the band plan for the purpose of coexistence of access and in-house PLC systems, in which 1.6–10 MHz is assigned exclusively (or with priority) for access, and 10–30 MHz is assigned in-house with priority [6]. There are already some commercial products which provides 10–45 Mbps using this expanded bandwidth. PLC with this wide frequency range is called *Wide-Band PLC.*

2.2 Chimney Approach and Low-Peak Approach

In wide-band PLC, the interference to the radio broadcasting and communications should be avoided. In order to ensure preoccupancy of these wireless systems, there are two approaches, called chimney approach and low-peak approach [1]. Figure 1 illustrates the conceptual frequency spectrums of these approaches.

As shown in the figure, in the chimney approach, a PLC signal spans in the strips of frequencies where wireless systems do not use. In other words, PLC systems do not emit power in the range where wireless users occupy, such as broadcasting and radio communication bands. As the results, the frequency spectrum of a PLC system with chimney approach is discontinuous and looks like a train of chimneys in frequency domain. For the systems with chimney approach, it is

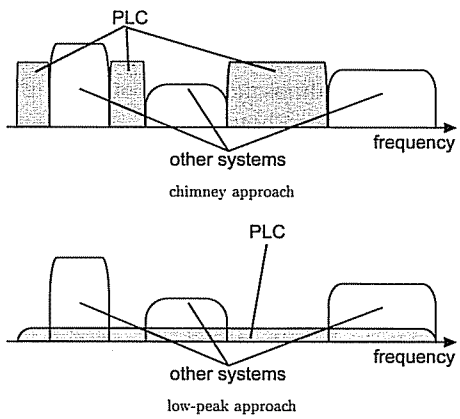


Fig. 1 Chimney approach and low-peak approach.

easy to show the "innocence" to conventional wireless systems, and also they are robust for the interference from wireless systems using the frequencies outside the chimneys. On the other hand, the systems may influence (and be influenced) to (by) wireless systems that uses frequency in a chimney unexpectedly.

The latter approach, low-peak approach intends to spread the signal power over the whole (wide) frequency range in order to make the signal power spectral density (psd) negligibly smaller than that of the wireless system. With this approach, PLC systems are robust to narrow band interference and ensure small interference without knowledge of the frequencies used by wireless systems. However, when a receiver (or a transmitter) of a wireless system is located very near to the power-lines, PLC signals may cause (or be contaminated) strong interference to (or from) the wireless system irrespective of its frequency.

3. Noise in PLC

3.1 Classification of Noise

The noise in power-lines is mainly caused by electric appliances connected to the lines [7]–[14]. For design and analysis of conventional communication systems, stationary additive white Gaussian noise (AWGN) is often used as a model of noise. In PLC, however, the statistical behavior of this man-made noise is quite different from that of stationary AWGN. The communication systems designed on the conventional noise model may not achieve good performance under this peculiar noise environment. The careful consideration on the statistical behavior of the noise in PLC is necessary.

The noise in power-lines can be assumed to be the sum of several classes of noise [9], [15], [16] as listed below.

1. **continuous noise:** The level of this class of noise does not change abruptly. The main cause is summation of numerous noise sources with low power. Its psd is decreasing with frequency.

1.1 stationary continuous noise: This subclass of continuous noise is time invariant. Its power is almost constant over time in terms of minutes to hours.

1.2 cyclic stationary continuous noise: This subclass of noise changes its level continuously and cyclically synchronous to the mains frequency (50 or 60 Hz in Japan). Many electric appliances often emit this non-stationary but non-impulsive noise.

2. impulsive noise: This class of noise has short (some micro seconds to milliseconds) duration and large amplitude. The main cause is switching devices.

2.1 cyclic impulsive noise, synchronous to mains: This class of impulsive noise has the frequency the same to the mains frequency. The main sources of this type of impulses are power devices and electric dimmers.

2.2 cyclic impulsive noise, asynchronous to mains: Impulses of this class often has repetition rate much higher than the mains frequency, between 50–200 kHz. These impulses are often caused by switching power supplies.

2.3 asynchronous impulsive noise: This is the result of a switching transient on the power-lines. The arrival time is arbitral and unpredictable. The levels of this asynchronous impulses often tend to be high but possibility of the occurrences is not so high as former cyclic impulses.

3. narrow-band noise: This class of noise has narrow bandwidth and almost constant amplitude. The main cause of this class of noise is ingression of the radio waves of broadcasting and radio communication stations. Thus the frequencies and other statistical features of this class of noise are predictable.

The classification above shows that the characteristic of the noise in power-lines is not stationary (except stationary continuous noise and narrow-band noise). Therefore, a model that can describe the statistics of instantaneous value of the noise is necessary.

3.2 Model of Narrow-Band PLC Noise

According to former experiments and measurements, the dominant components of the noise in narrow-band PLC are the first three classes: stationary continuous noise (1.1), cyclic stationary continuous noise (1.2), and cyclic impulsive noise synchronous to mains (2.1). The noise represented by sum of these three components can be assumed as cyclo-stationary process. With this assumption, a mathematical model of the noise is possible, and without a huge database of measured noise waveforms, a simple program can easily generate noise waveforms that represent the features of actual noise in power-lines. This subsection is a brief introduction of this noise model.

In this model, the noise in narrow-band PLC is assumed to be cyclo-stationary additive Gaussian noise whose mean is zero. Based on [16], the time-frequency dependent variance of noise waveform $n(t)$ is represented as

$$\sigma^2(t,f) = \sigma^2(t)a(f) \tag{1}$$

where

$$\sigma^2(t) = \sum_{i=1}^{3} A_i |\sin(2\pi/T_{AC}t + \theta_i)|^{n_i} \tag{2}$$

and

$$a(f) = \frac{e^{-af}}{\int_{f_0}^{f_0+W} e^{-af} df}. \tag{3}$$

In the above equations, T_{AC} is a cycle duration of the mains alternating current (AC), typically 1/60 or 1/50 seconds. In Eq. (1), the function $\sigma^2(t)$ denotes the instantaneous power of the noise, and $a(f)$ represents the noise psd normalized by the total noise power in the frequency range f_0 to f_0+W, in which the communication system is discussed in Sect. 5.

The instantaneous power of the noise (2) can be represented by a set of parameters, (A_1, A_2, A_3) for amplitude, $(\theta_1, \theta_2, \theta_3)$ for phase, and (n_1, n_2, n_3) for impulsiveness or power concentration in time domain. Now let the first term of (2) be for the noise of the class 1.1, the second for the class 1.2, and the third for the class 2.1; then parameters θ_1 and n_1 are not needed i.e.,θ_1 is arbitrary and n_1 is zero. As the result, seven parameters are needed for (2) and additional one parameter a is used for the feature of noise in frequency domain. Figure 2 shows a snapshot of measured noise waveforms and the computer generated waveform with the parameters given in Table 1, which are extracted from the measured noise waveforms. The variance in time domain, $\sigma^2(t)$ with these parameters is shown in Fig. 3.

There may be various ways to assign values for the

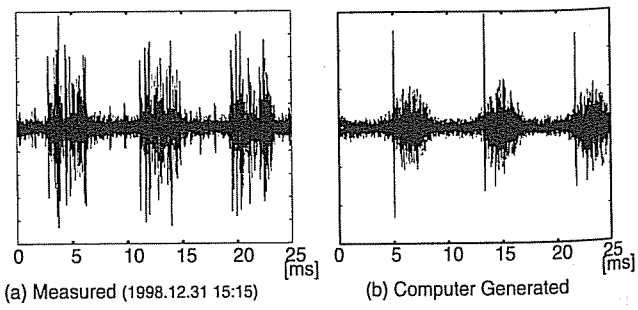


Fig. 2 Snap-shot of measured and generated noise waveforms.

Table 1 An example of noise parameters.

A_1	A_2	θ_2	n_2
0.13	0.26	128[deg]	9.3

A_3	θ_3	n_3	a
16	161[deg]	6.9×10^3	8.8×10^{-6}

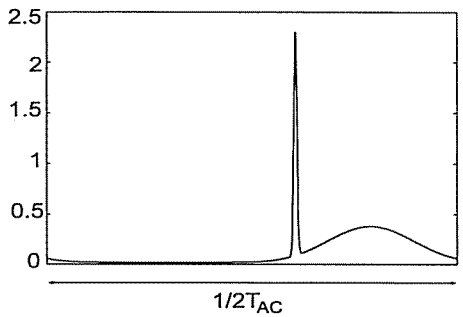


Fig. 3 Approximated variance of noise.

parameters from the measurement results. As an example an intuitive method is introduced in [16], and it is shown that all parameters converge with the observation of 40–50 cycles duration of mains AC, i.e., less than one second.

3.3 Remarks on PLC Noise

The model of PLC noise, described in the preceding subsection is for narrow-band systems. Noise in wide-band PLC systems has different features. For example, continuous noise and cyclic impulsive noise decrease with frequency, and narrow-band noise tends to act an important role.

Communication systems designed without accurate knowledge of this peculiar noise environment may not achieve good performance. Though there are many reports about the noise statistics for wide-band PLC noise, most of them describe only power spectrum densities and intensity distributions, which are time-averaged features of the noise. The experiment and measurement of wide-band PLC noise to acquire the statistical features of instantaneous value are necessary, and besides, construction of tractable mathematical model of wide-band PLC noise is required.

As discussed above, noise in PLC systems is not conventional AWGN, and many reports claim that this non-Gaussian noise is the cause of low quality of PLC systems. On the contrary, the fact that Gaussian distribution has the largest differential entropy implies that the PLC under the non-Gaussian noise may achieve better performance than that under AWGN of the same power. In fact, in [17] Miyamoto et al. show that the performance of the system under impulsive noise environment exceeds that under AWGN with proper consideration of noise statistics, while conventional receiver structure optimized for AWGN suffers large performance degradation. It thus can be expected that PLC systems still have large room for performance improvement, if the behavior of power-line noise is clarified and taken into account in system design.

4. Channel Characteristics of Power-Lines

The appliances connected to power-lines with power outlets are not only source of noise, but also cause of fluctuation of impedance of power-lines. For example, if an appliance has noise filter to block noise to/from power-lines, it may short-circuit lines from the viewpoint of signal transmission. If an appliance has inductors and capacitors connected to power-lines, those devices may form a resonant circuit, which has sharp peaks and notches in the frequency response of power-lines. In addition, many appliances has active devices which turn on and off according to the mains voltage. This can be the cause of time variation of line impedance, which is often synchronous to mains frequency and can be modeled as cyclo-stationary process. As the results of these phenomena, power-lines should be assumed as frequency selective channel.

The features described above are common in narrow-band systems and wide-band systems. There are some specific characteristics in wide-band systems, such as high propagation loss because of the capacity between power-lines, especially in in-house systems. In addition, the effects of multi-path caused by reflections of signals at branches of lines are larger in wide-band PLC.

In [18], Yamamoto et al. report results of measurement and show that fluctuation of power-line impedance in time is large in narrow-band PLC under 500 kHz, but the effect of fluctuation is smaller in wide-band systems. Especially in the range between 1 MHz to 10 MHz power-line has steady impedance compared to other frequency ranges. They also find that, in the frequency range above 10 MHz, electric appliances connected to power-lines have little influence to power-lines because of high inductance of cables between the outlets to the appliances.

5. Modulation and Error Control

Until recently, simple and even old-fashioned modulation schemes had been used for PLC. For example, in Japan, the current (as of beginning of 2001) regulation allows only simple ASK, PSK, FSK besides DS-SS with a relatively small spreading factor. Among them, the first three modulation schemes are basically designed for stable and low noise radio environment, and the latter (DS-SS) is not robust under strong impulsive noise and narrow-band noise. It is evident that these modulation schemes do not match PLC.

The property of power-lines as communication media is not flat in frequency and non-stationary in time. Thus the modulation schemes for PLC of next gen-

eration should have the capability to adapt this non-uniform and dynamically changing channel. For this purpose, a multi-carrier modulation scheme such as OFDM with multi-dimensional (time and frequency domain) coding is a prospective candidate. In the next section, a simple OFDM scheme (without error correction coding) is shown as an example.

The idea to map information according to the channel state information is popular in radio communication, and there are quite a few papers on this topic. In many of these studies, the channel state is assumed to be symmetrical, i.e. the information of signal-to-noise ratio of each frequency is common at the both end of communication. It should be noted that this symmetry is, however, not ensured in PLC. The characteristic of signal-to-nose ratio of each frequency in PLC is often dominated by noise source located near to a receiver, and the transmitting side may be influenced by different noise sources with different noise spectra. Therefore, the feedback loop to report channel state information from receiving terminal is necessary for adaptive modulation and coding schemes.

5.1 System Model

In this section, as an example, perfromance analysis of a PLC system is discussed on this cyclo-stationary Gaussian noise modeled in 3.2, in which noise waveform changes its statistical characteristics periodically at every half cycle of the power supplying AC, i.e., $T_{AC}/2$. In frequency domain, let the frequency band used for communication be f_0 to $f_0 + W$. Then, modulation can be represented by a mapping of data to the time-frequency space of the area $(T_{AC}/2) \times W$. With the OFDM modulator of symbol duration T_s and M sub-carriers of the bandwidth $\Delta = 1/T_s$, the time-frequency space is paved with a set of cells of the size $T_s \times \Delta$, as in Fig. 4. For convenience, let $W/\Delta = M$ and that $T_{AC}/2T_s = K$ is an integer.

With the equivalent low pass model of the carrier frequency f_0, the received signal after the bandpass filter of the receiver is represented as

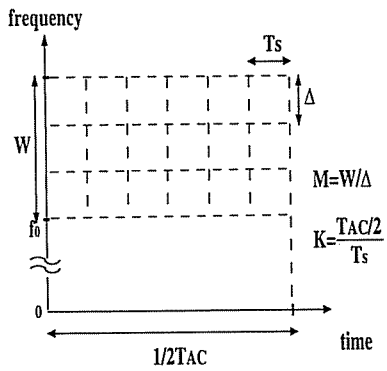


Fig. 4 Time-frequency space for communication.

$$r(t) = s(t) + n(t), \tag{4}$$

where

$$s(t) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} \sqrt{P/M} b_{k,m} g(t - kT_s) e^{j2\pi(m+1/2)\Delta t}. \tag{5}$$

In the above equation, P is the signal power, $b_{k,m} \in \{\pm 1, \pm j\}$ is the QPSK symbol in the k-th symbol duration at the m-th sub-carriers, and $g(t)$ is the symbol pulse shape. For simplicity, let $g(t)$ be the rectangular pulse:

$$g(t) = \begin{cases} 1 & 0 \le t \le T_s \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

The noise component $n(t)$ of (4) is cyclo-stationary additive Gaussian noise whose mean is zero and the time-frequency dependent variance is given by (1).

The received signal is demodulated by the correlation demodulator shown in Fig. 5. If synchronization is assumed to be perfect, then the sample for the k-th symbol at $t = kT_s$ of the branch corresponding to the m-th sub-carriers becomes

$$\begin{aligned} r_{k,m} &= [r(t) e^{-j2\pi(m+1/2)\Delta t} * g(-t)]|_{t=kT_s} \\ &= s_{k,m} + n_{k,m}, \end{aligned} \tag{7}$$

where $*$ denotes convolution operation. The notations $s_{k,m}$ and $n_{k,m}$ are for the signal and noise components for the k-th symbol duration and m-th sub-carriers.

5.2 BER Performance

The signal component of (7), $s_{k,m}$, is

$$s_{k,m} = \int_{-\infty}^{\infty} s(t) g(t - kT_s) e^{-j2\pi(m+1/2)\Delta t} dt$$

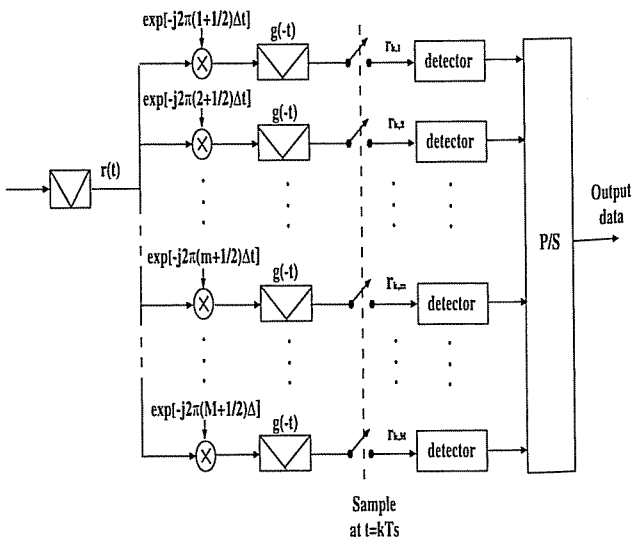


Fig. 5 Demodulator.

$$= \int_{kT_s}^{(k+1)T_s} s(t)e^{-j2\pi(m+1/2)\Delta t}dt$$
$$= \sqrt{P/M}T_s b_{k,m}. \quad (8)$$

Similarly, $n_{k,m}$ is represented as

$$n_{k,m} = \int_{-\infty}^{\infty} n(t)g(t-kT_s)e^{-j2\pi(m+1/2)\Delta t}dt. \quad (9)$$

Since this is the linear transformation of the zero mean complex Gaussian noise $n(t)$, this sample is also zero mean complex Gaussian, and its variance is

$$\sigma_{k,m}^2 = E[n_{k,m}^2]$$
$$= a\left(f_0 + \left(m+\frac{1}{2}\right)\Delta\right)\int_{kT_s}^{(k+1)T_s} \sigma^2(t)dt. \quad (10)$$

In addition, average noise power in the duration $0 < t < T_{AC/2}$ is calculated by

$$P_n = \frac{2}{T_{AC}}\int_{T_{AC}/2} \sigma^2(t)dt. \quad (11)$$

From the above development, the BER for $r_{k,m}$ is

$$P_{k,m} = \frac{1}{\sqrt{2\pi}\sigma_{k,m}}\int_0^{\infty} e^{-\frac{(x+\sqrt{P/M}T_s)^2}{2\sigma_{k,m}^2}}dx$$
$$= \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{PT_s^2/M}{2\sigma_{k,m}^2}}\right), \quad (12)$$

where $\mathrm{erfc}(x)$ is complementary error function.

5.3 Numerical Examples

Numerical examples are given for the noise parameters in Table 1 and the system parameters in Table 2.

From (12), BER of each cell is calculated with $P/P_n = 5$. Figure 6 shows BER performance as functions of time. In this figure, the number of sub-carriers is four, and thus the number of symbols per $T_{AC}/2$ is 512. From this figure, it can be confirmed that the BER is time and frequency dependent. In time domain, the BER changes according to $\sigma^2(t)$ shown in Fig. 3, and in frequency domain, BER is higher in lower frequency (smaller m) as the result of the exponential noise spectrum.

The cumulative distribution of BER for various M is derived as shown in Fig. 7, where the vertical axis is the ratio of cells whose BER is lower than the value Θ of the horizontal axis. Since the BER performance of PLC system is not uniform in time and frequency and predictable with the knowledge of noise statistics, it is possible to improve BER performance by omitting cells with higher noise level. From this viewpoint, the cumulative distributions can be understood as the curves to find the percentage of remaining cells after the erasure to ensure the BER on the horizontal axis, Θ. From this reason, we call Θ as guaranteed BER.

Since the number of sub-carriers, M, affects the BER distribution, the overall performance of the system is dominated by the selection of M. Figure 8 shows the percentage of cells whose BER is smaller (better) than a given required value Θ as a function of M. From this figure, it is known that there are optimum values of M for given noise statistics and required guaranteed BER, Θ. When performance requirement is loose, or the guaranteed BER is large (10^{-1}), the performance is insensitive to the number of sub-carriers and takes

Table 2 System parameters.

Cyclic-duration of AC	T_{AC}	1/60=16.67ms
Lowest frequency	f_0	204.24 kHz
System bandwidth	W	245.76 kHz
Number of cells	MK	2048

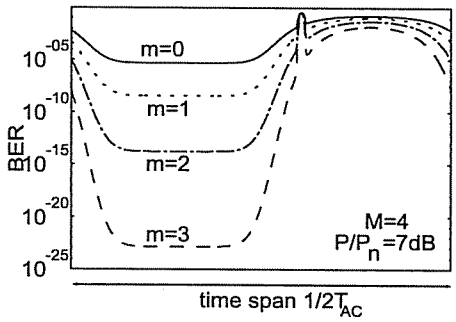


Fig. 6 BER distribution on time and frequency.

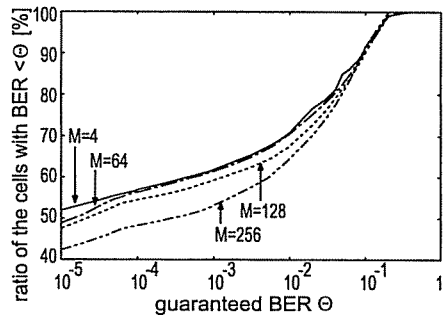


Fig. 7 Cumulative distribution of BER.

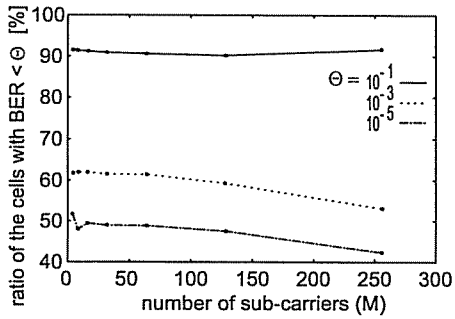


Fig. 8 Influence of number of sub-carriers.

the optimum value at the largest M, i.e., $M = 256$. On the contrary, when smaller BER (less than 10^{-3} or less than 10^{-5}) should be guaranteed, the larger number of sub-carrier has worse performance.

6. Multiple Access

In the case of PLC for access networks, low-voltage grid serves households under the same step-down transformer. When PLC systems are used in-house, the same pair of power-lines are used as a common communication media for PLC equipments connected to the lines. In such environment, it is necessary to have strategy of sharing the power-lines used as a communication media by more than one pair of terminals, i.e. multiple access scheme.

There are several different ways in which multiple users can send and receive data through the same power-lines, and they can be classified into two groups. Random access is in the first group. In this scheme data are sent in packets, and all the packets of each terminal are sent autonomously to the same power-line channel. On the contrary, the schemes of the second class subdivide a power-line channel into a number of sub-channels and assign them to terminals.

One of the most popular methods of random access is Carrier Sense Multiple Access (CSMA). According to this protocol, a terminal sends a packet after listening the channel and confirming that the channel is not used by other terminal. With this scheme, a central control station is not required and addition and deletion of a terminal to a network is easy. Because of these advantages, CSMA is often used in LAN systems and also in many PLC systems.

CSMA is by nature a protocol for stable wire communication, where noise level, propagation loss, and delay are small. When CSMA is simply applied to PLC, performance degradation is unavoidable because of high probabilities of miss-detection and false alarm of packets caused by strong noise and fluctuation of transmission characteristics of power-lines. In addition, quality of power-line channel depends on location, which causes hidden terminal problem. This also degrades the throughput performance.

The second group of multiple access schemes, in which sub-divided channels are assigned to terminals includes access schemes, such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA). Among these three strategies, FDMA is not suitable because channel performance of PLC strongly depends on frequencies. The equipment to have common time clock excludes TDMA for PLC. On the contrary, CDMA has attractive features for PLC: all signals can use the same frequency range at the same time without common clock and central controller. Especially, CDMA ALOHA [20], which is the combination of CDMA and packet random-access, is a promising scheme for PLC.

In CDMA, a channel is sub-divided into a number of orthogonal (or quasi-orthogonal) code channels. In addition to conventional direct-sequence (DS) CDMA and frequency-hopping (FH) CDMA, multi-carrier (MC) CDMA [21], in which spreading code spans in frequency domain over subcarriers of OFDM modulation, is advantageous because of the good consistency with the requirements on modulation scheme for PLC.

7. Improvement of Power-Lines

Discussions above assume that PLC use power-lines as they are. And the difficulties of PLC arise from the fact that specifications of power-lines do not consider communications. Especially in the case of in-house PLC, if an electric appliance completely short-circuits power-lines in terms of the signal frequency, it is almost impossible to realize reliable communications on the lines.

In the case of wireless communication systems, many efforts are paid to ensure the radio environments comfortable. Strict regulations of EMC for equipments that emit radio wave are examples of them. Retransmission systems of radio and mobile phone signals into tunnels and underground shopping areas are other examples. If PLC should be an infrastructure of information ages, it is not enough just to study PLC systems for given power-line channels. Efforts to improve the qualities of power-lines as a communication media are also necessary. For this purpose, design of power-lines and electric appliances considering PLC is required. In addition, it is strongly needed to develop cheap and small filters that suppress noise and isolate low-impedance equipments from power-lines.

8. Conclusion

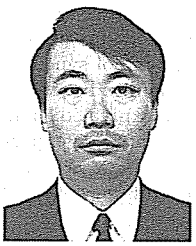
Recent attentions that PLC is taking are not only of communication engineers but also of the people in utilities. PLC is going to play an important role in communication systems. Though main reasons of their interest are of economy, PLC systems also have many interesting technical features from the viewpoint of communication engineering, such as non-stationary non-white noise and propagation characteristics, which are discriminative from conventional communication systems. For the realization of robust, reliable, and high-speed PLC systems, investigations and considerations of these peculiar features of power-lines are not avoidable. Such PLC systems had been almost impossible because of the highly sophisticated signal processing necessary. The recent revolutionary progress in digital signal processing and radio communication, however, makes this possible.

This manuscript briefly introduces the back-

grounds of PLC, and features of power-lines as a communication media, and technical challenges for future PLC. As mentioned above, PLC is necessary, interesting and possible to realize. It is great honor and appreciation of the author if this manuscript could stimulate an interest of a reader to PLC.

References

[1] S. Feindt and U. Leicht, "European PLC market observatory," PALAS Report, Deliverable 1, June 2000.
[2] http://palas.regiocom.net/
[3] http://www.sigma-consultants.fr/plcforum/index.htm
[4] http://www.homeplug.org/
[5] W. Matsumoto, "The power line communication modem by the dispersed tone modulation method which is applied muticarrier data transmission technology," IEICE Trans., vol.J84-B, no.1, pp.38–49, Jan. 2001.
[6] ETSI TS 101 867, v1.1.1, "PLT; Coexistence of access and in-house powerline systems," Nov. 2000.
[7] The Ministry of Posts and Telecommunications, "Interim report of the study group for power line communications," March 1985.
[8] The Ministry of Posts and Telecommunications, "Final report of the the study group for power line communications," July 1986.
[9] D. Hines, J. Dickinson, P. Nicholson, R. Lehnert, H. Hrasnica, A. Haidine, M. Stantcheva, M. Langhof, and U. Leicht, "Technology inventory and development roadmap," PALAS Report, Deliverable 2, June 2000.
[10] R.M. Vines, H.J. Trussell, L.J. Gale, and J.B. O'Neal, Jr., "Noise on residential power distribution circuits," IEEE Trans. Electromagn. Compat., vol.EMC-26, no.4, pp.161–168, Nov. 1984.
[11] M. Tanaka and R. Someya, "The noise characteristics and transmission characteristics on data transmission using power line," IEICE Trans., vol.J69-B, no.10, pp.1147–1149, Oct. 1986.
[12] M.H.L. Chan and R.W. Donaldson, "Amplitude, width, and interarrival distributions for noise im-pulses on intrabuilding power line communication networks," IEEE Trans. Electromagn. Compat., vol.31, no.3, pp.320–323, Aug. 1989.
[13] S. Tachikawa, H. Hokari, and G. Marubayashi, "Power line data transmission," IEICE Technical Report, SSTA89-7, March 1989.
[14] O.G. Hooijen, "A channel model for the low-voltage powerline channel; measurement- and simulation results," Proc. 1997 International Symposium on Power-Line Communications and its Applications, pp.51–56, 1997.
[15] H. Niwa, O. Ohno, M. Katayama, T. Yamazato, and A. Ogawa, "A Spread spectrum system with dual processing gains designed for cyclic noise in power line communications," IEICE Trans. Fundamentals, vol.E80-A, no.12, pp.2526–2533, Dec. 1997.
[16] M. Katayama, S. Itou, T. Yamazato, and A. Ogawa, "Modeling of cyclostationary and frequency dependent powerline channels for communications," Proc. 2000 International Symposium on Power-line Communication and its Applications, April 2000.
[17] S. Miyamoto, M. Katayama, and N. Morinaga, "Design of TCM signals for class-A impulsive radio noise environment," IEICE Trans. Commun., vol.E78-B, no.2, pp.253–259, Feb. 1995.
[18] S. Yamamoto, S. Tsuzuki, and Y. Yamada, "Measurement of characteristic of indoor power-line channel," IEICE Technical Report, SST2000-55, Dec. 2000.
[19] K. Sugimoto, M. Katayama, T. Yamazato, and H. Okada, "Performance of an OFDM communication system under a frequency and time dependent power-line channel," Proc. 2001 International Symposium on Power-line Communication and its Applications, April 2001.
[20] T. Yamazato, A. Ogawa, M. Katayama, and A. Jamalipour, "Tutorial: Introduction to CDMA ALOHA" Tutorial Note, TI-13, IEEE Global Telecommunications Conf., Nov. 1998.
[21] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE Commun. Mag., vol.35, no.12, pp.126–133, Dec. 1997.
[22] M. Katayama, "Technical challenges for the realization of robust reliable and high-speed power-line communication systems," IEICE Technical Report, SST2000-60, Dec. 2000.



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