Correlations of noise waveforms at different outlets in a power-line network

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Abstract— **This manuscript discusses the relationships of noise waveforms measured at different outlets in a three-wire single-phase (one neutral and two live conductors) power-line network. As a result of experimental measurements, it is confirmed that instantaneous noise voltages at two different outlets have high correlations if the outlets are connected to the same live conductor in a distribution board, while the outlets for the different live conductors provide noise waveforms with low correlations. It is also shown that the instantaneous noise powers and cyclic averaged noise powers as time functions have large correlations even at a pair of outlets connected to the different live conductors. The correlation coefficients for instantaneous voltages and powers are also calculated as the frequency functions.**

Keywords: Power-Line, Noise Characteristics, Correlation.

I. Introduction

The power-lines are not designed for communications, hence their characteristics are quite different from those of communication cables. One of the most peculiar aspects is the fact that noise is non-stationary, non-white, and non-Gaussian. These non-flat features of noise cause performance degradations in the communication systems designed under the stationary white Gaussian noise assumption.

To clarify the characteristics of power-line noise, measurements and the examinations performed in former studies, and many interesting features have been reported. For example, power-line noise has cyclo-stationary features synchronous to the mains AC voltage[1]. For narrow-band PLC systems, the cyclo-stationary noise model is proposed in [2]. Zimmerman and Dostert discussed the classification and modeling of impulsive noise[3]. In [4], a noise waveform at an outlet is frequency-divided into subbands, and autocorrelation and cross correlations of noise waveforms in these subbands are analyzed.

In these former studies, a noise waveform is measured at an outlet in each experiment. In many wireless systems, thermal noise dominates noise statistics, and the noise waveforms at a transmitter and a receiver are independent. In PLC systems, however, the dominant factors of noise sources are electrical appliances connected to a power-line network, and it can be expected that the noise waveforms at different outlets have correlations. These correlations of noise waveforms at different locations in a power-line network can be used to improve the performance of PLC systems. For example, if noise waveforms at a transmitter and a receiver have correlations, transmitter can select frequencies and time-slots with low estimated noise-level at the receiver.

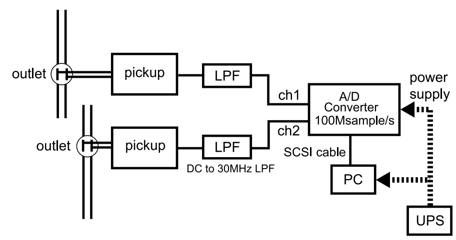

Fig. 1. Measurement System

This paper introduces some results of experimental measurements, in which noise waveforms are taken simultaneously at two different outlets in a three-wire single-phase (one neutral and two live conductors) power-line network. Examples of correlation characteristics are calculated for the noise waveforms on the same(different) live conductors.

II. The measurement system

Figure 1 shows the measurement system used in this study. The system consists of a pair of pickups and anti-aliasing low-pass filters and an A/D converter with a PC. The A/D converter and the PC are isolated from the mains power-line network and are power-supplied by a battery-driven UPS(Uninterruptible Power Supply) in order to avoid the influence to noise waveforms on a power-line network.

As shown in Fig.2, each pickup has two circuits, Circuit-W and Circuit-N, with a switch. The parts for Circuit-W are selected for wide-band(HF) PLC, while Circuit-N is designed for narrow-band(below 450kHz) PLC. The list of the circuit elements of the pickups is given in Table I and frequency characteristics of these circuits are shown in Fig.3.

III. Measurement setups

The experimental measurements are made at several locations. In this manuscript, examples are shown based on the

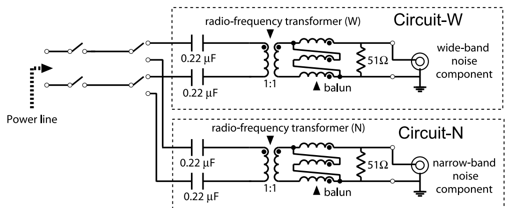

Fig. 2. Inside a pickup[4].

TABLE I
CIRCUIT ELEMENTS.

Component	Model	Specifications
RF transformer (for Circuit-N)	JPC ELH-01	Turn ratio 1:1
RF transformer (for Circuit-W)	-	Turn ratio 1:1 Core : TDK HF70
Balun	-	5 turns Core : TDK HF70
Low Pass Filter	Mini-Circuit BLP-30M	DC to 30MHz LPF
A/D Converter	PAVEC DF-4P2HW-1066 001401129	Range ±1.28V Resolution:12bits rate 100Msps

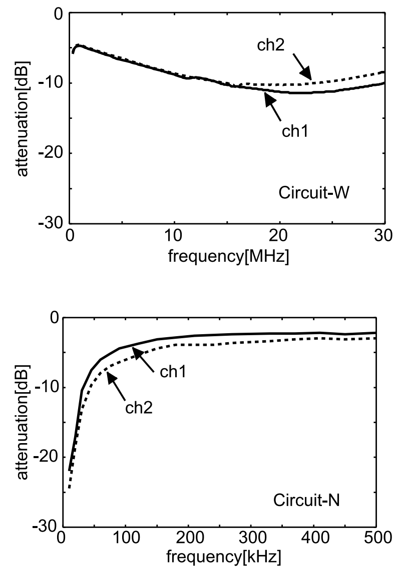

Fig. 3. Frequency response characteristics of circuit-W and circuit-N.

results at a ten-storied building of Nagoya University. Three outlets on the same floor are selected for the measurements. The outlets are cabled in star topology to a panel board as a center. As shown in Fig.4, both Outlet-1 and Outlet-3 are connected to the same live conductor (L1) and the neutral conductor (N), while Outlet-2 are connected to the other live conductor (L2). Though all outlets on the floor are connected to one of the two live conductors and the neutral for 100V, inverter driven ceiling floor lamps and air conditioners are connected to L1 – L2 for 200 V power supply.

The noise waveforms are taken on a weekday afternoon when many noise-producing appliances are active. The measurements are made for four different cases as shown in Table II. In Case-A and Case-B only the pickups of measurement systems are connected to the outlets. Thus noise comes from the panel board. Figure 5 shows a snap shot of the noise waveform taken at Outlet-1, and its power spectrum density is shown Fig.6. Since the noise floor of the measurement system is -115dBm, Fig.6 implies that the power of noise concentrates in the frequency range below 15MHz. In addition to the pickup, vacuum cleaner is also connected to Outlet-1 as a noise source in Case-A' and Case-B'. An example of the snap-shot at Outlet-1 is shown in Fig.7.

For each case, both wide-band and narrow-band noise component are measured using Circuit-W and Circuit-N, respectively.

IV. CORRELATIONS OF NOISE WAVEFORMS MEASURED SIMULTANEOUSLY AT DIFFERENT OUTLETS

Let the noise waveform at the ch-1 of the A/D converter as $n_1(t)$ and at the ch-2 as $n_2(t)$. In each measurement, the waveforms at both input are sampled simultaneously. If the sampling is made every δ[s] over the duration T[s], the A/D converter stores a pair of T/δ samples, which are denoted as $n_1(i\delta)$ and $n_2(i\delta)$, for i=0, 1, 2, ..., $T/\delta - 1$.

A. Correlations of the instantaneous voltages

To examine the correlation of $n_1(t)$ and $n_2(t)$, the scatter diagrams of them are plotted in Figs.8 – 10. If the instantaneous noise voltages at the outlets at the same instant are identical, the scatter diagram becomes a linear line. On the contrary, if $n_1(t)$ and $n_2(t)$ are independent, the diagram results in a rectangular.

Figure 8 is the scattering diagram of the noise voltages in Case-A with Circuit-W. This figure shows large correlations of two noise voltages taken at the different locations, Outlet-1 and Outlet-3. In contrast, in Fig.9 for Case-B with Circuit-W, the noise voltages at Outlet-1 and Outlet-2 have small correlations. Since the lengths of the cables for Outlet-2 and Outlet-3 from the panel board are almost the same, the propagation loss by cable is not the cause of the difference. It means that the instantaneous noise voltages at different mains phases, or different live conductors, have small correlations. In fact, the scattering diagram for Case-A' shows that the noise voltage at the outlet with a strong noise source still has correlations with the noise voltage at different outlet of the same mains phase.

In order to clarify the degrees of similarity between the noise waveforms measured at different outlets, the correlation coefficient of the instantaneous noise voltages is calculated. The correlation coefficient ρ between $n_1(i\delta)$ and $n_2(i\delta)$ is defined as

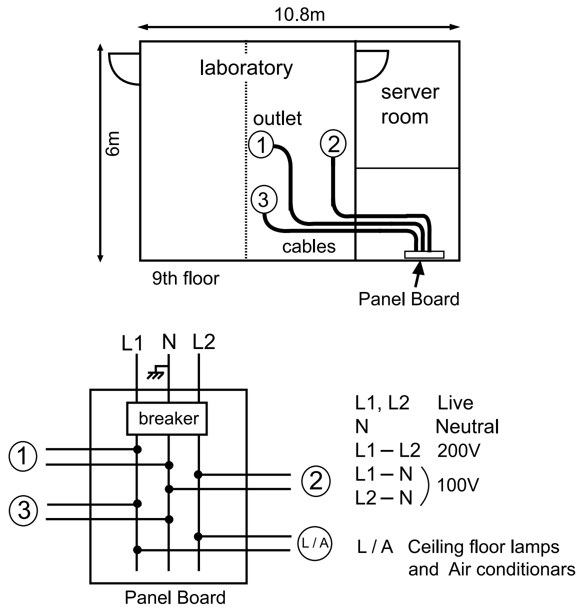

Fig. 4. Cabling structure

TABLE II
MEASUREMENT CONDITIONS

	Outlet a pair	Noise Source on Outlet-1
Case-A	Outlet-1 Outlet-3	None
Case-B	Outlet-1 Outlet-2	
Case-A'	Outlet-1 Outlet-3	Vacuum Cleaner Hitachi XV-PE9 (350-600W)
Case-B'	Outlet-1 Outlet-2	

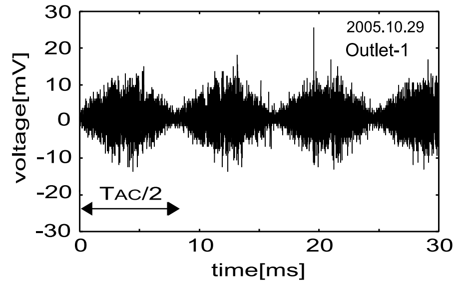

Fig. 5. A snap-shot of a noise waveform sampled at Outlet-1 (pickup:Circuit-W)

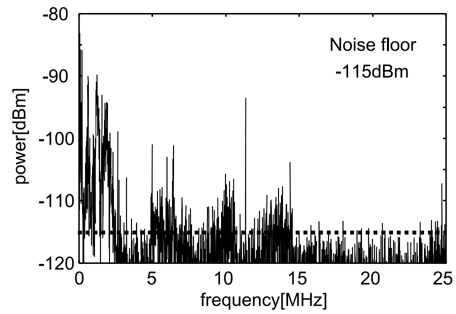

Fig. 6. Noise spectrum sampled at Outlet1(pickup:Circuit-W)

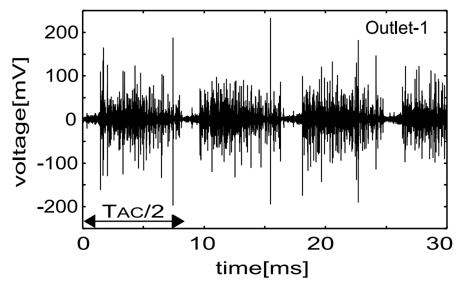

Fig. 7. A snap-shot of a noise waveforms at Outlet-1 with a vacuum cleaner(pickup:Circuit-W)

$$\rho = \frac{\sum_{i=0}^{T/\delta-1}(n_1(i\delta)-\overline{n_1(i\delta)})\cdot(n_2(i\delta)-\overline{n_2(i\delta)})}{\sqrt{\sum_{i=0}^{T/\delta-1}(n_1(i\delta)-\overline{n_1(i\delta)})^2}} \times \frac{1}{\sqrt{\sum_{i=0}^{T/\delta-1}(n_2(i\delta)-\overline{n_2(i\delta)})^2}}\,, \qquad (1)$$

where $\overline{n_1(i\delta)}$ and $\overline{n_2(i\delta)}$ are the average values of all T/δ samples of $n_1(i\delta)$ and $n_2(i\delta)$, respectively. Since the noise waveforms have no DC component, both $\overline{n_1(i\delta)}$ and $\overline{n_2(i\delta)}$ are negligible.

Correlation coefficients are calculated for both wide-band noise components and narrow-band noise components in all four cases of Table II. For the calculation, sampling is made over the duration of $T = 1$ second with the sampling rate of $1/\delta = 1.0 \times 10^8$ samples/second. Thus for a correlation coefficient, a pair of 100M samples of noise voltages are used. For the calculation on the narrow-band noise, the pair of the samples are first numerically band-limited in the range 50kHz to 450kHz by a FIR filter with 3545-taps.

The results of the calculation are listed in Table III. From this table, it can be concluded that instantaneous noise voltages have a large correlation coefficient ρ if they are taken from the outlets of the same mains phase, or of the same live conductor. This conclusion stands even in the extreme case (Case-A') where one of two noise waveforms is observed at the outlet with the strong noise source.

This high correlation of instantaneous noise waveforms at different outlets is based on the fact that the outlets are connected to the same noise sources via the same live conductor at the panel board. The difference of the noise waveforms at the outlets reflects the difference of transmission characteristics between the outlets and the noise sources.

On the contrary, if the noise voltages are taken from the outlets of the different mains phase, the noise waveforms have a small (almost zero) correlation coefficient. It means that the cross-coupling between two live conductors is very small in a three-wire single phase power-line system.

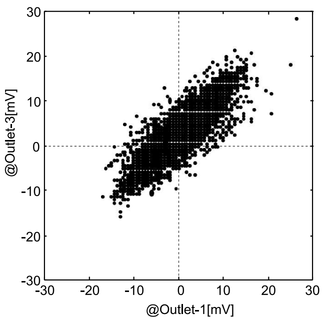

Fig. 8. Scattering diagram for Case-A with Circuit-W

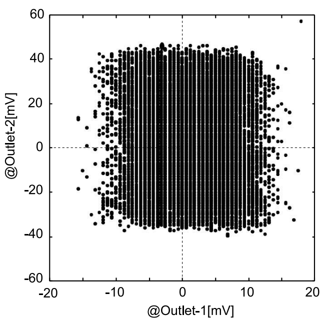

Fig. 9. Scattering diagram for Case-B with Circuit-W

The features described above can be observed for both wide-band and narrow-band noise. According to the results in Table III, wide-band noise components has larger coefficient ρ than narrow-band noise components. The authors are now performing additional measurements in various environment to confirm if this is a common feature of power-line channels. The results will be presented at the symposium.

B. Correlations of the instantaneous powers

The power-line noise is not stationary and noise powers vary as time functions. If the transmitter can not know the instantaneous noise voltage at the receiver but if it can estimate the power of the noise at the receiver, the estimate still can be used for performance improvement. For this reason, in this subsection we discuss the correlation coefficient of the instantaneous noise powers at different outlets, which is defined as

$$\rho_{power} = \frac{\sum_{i=0}^{T/\delta-1}(n_1^2(i\delta) - \overline{n_1^2(i\delta)}) \cdot (n_2^2(i\delta) - \overline{n_2^2(i\delta)})}{\sqrt{\sum_{i=0}^{T/\delta-1}(n_1^2(i\delta) - \overline{n_1^2(i\delta)})^2}} \times \frac{1}{\sqrt{\sum_{i=0}^{T/\delta-1}(n_1^2(i\delta) - \overline{n_1^2(i\delta)})^2}} \ . \quad (2)$$

Note that $\overline{n_1^2(i\delta)}$ and $\overline{n_2^2(i\delta)}$ are average powers of noise, which are non-zero values.

The results of calculations are listed in Table III. According to this table, the correlation coefficients for instantaneous powers have large values, not only in Case-A and Case-A' but also in Case-B.

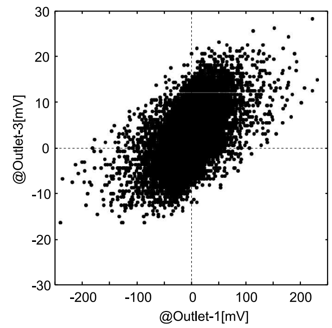

Fig. 10. Scattering diagram for Case-A' with Circuit-W

C. Correlations of the cyclic-averaged powers

It is known that the noise in power-line communications has cyclo-stationary features synchronous to the absolute value of the mains AC voltage. It means that the expectation of instantaneous noise power can be assumed as a periodic function with the frequency $2/T_{AC}$, where $1/T_{AC}$ is the frequency of mains AC.

If this assumption is made, the expectation of the noise power can be estimated as a periodic time function by a cyclic-average operation on the instantaneous noise power. Thus in this subsection, we consider the cyclic-averaged noise powers at different outlets, and discuss the correlations between them.

The cyclic-averaged noise power of $n_k(t)$ for $k = 1$ or 2 is defined as

$$\sigma_k^2(i\delta) = \frac{1}{2\lfloor T/T_{AC}\rfloor} \sum_{j=0}^{2\lfloor T/T_{AC}\rfloor-1} n_k^2(i\delta + jT_{AC}/2) \quad (3)$$
$$\text{for } i = 0,\ 1,\ \ldots,\ \lfloor T_{AC}/(2\cdot\delta)\rfloor - 1 \ ,$$

where $2\lfloor T/T_{AC}\rfloor$ is the number of samples corresponding to every $T_{AC}/2$ at duration T and $\lfloor T_{AC}/(2\cdot\delta)\rfloor$ means sample number at duration $T_{AC}/2$.

For example, the cyclic-averaged noise powers sampled at Outlet-1 and Outlet-2 are shown in Fig.11. From this figure, we can find a strong similarity of the cyclic-averaged noise powers even at the outlets on different mains phase.

In order to discuss the similarity between cyclic-averaged noise powers at different outlets, let us again calculate the correlation coefficient between them, which is defined as

$$\tilde{\rho} = \frac{\sum_{i=0}^{\lfloor T_{AC}/(2\delta)\rfloor-1}(\sigma_1^2(i\delta) - \overline{\sigma_1^2(i\delta)}) \cdot (\sigma_2^2(i\delta) - \overline{\sigma_2^2(i\delta)})}{\sqrt{\sum_{i=0}^{\lfloor T_{AC}/(2\delta)\rfloor-1}(\sigma_1^2(i\delta) - \overline{\sigma_1^2(i\delta)})}} \times \frac{1}{\sqrt{\sum_{i=0}^{\lfloor T_{AC}/(2\delta)\rfloor-1}(\sigma_2^2(i\delta) - \overline{\sigma_2^2(i\delta)})}} \ , \quad (4)$$

where $\overline{\sigma_k^2(i\delta)}$ for $k = 1$ or 2 is the average of $\sigma_k^2(i\delta)$ over $i = 0$ to $\lfloor T_{AC}/(2\cdot\delta)\rfloor - 1$.

TABLE III

CORRELATION COEFFICIENT OF NOISE MEASURED IN THE BUILDING

	ρ		ρ_{power}		$\tilde{\rho}$	
noise	wide	narrow	wide	narrow	wide	narrow
Case-A	86 %	79 %	77 %	99 %	98 %	99 %
Case-B	0.68 %	0.69 %	24 %	29 %	97 %	97 %
Case-A'	48 %	-28 %	24 %	30 %	69 %	84 %
Case-B'	-1.3 %	-1.8 %	8.7 %	10 %	78 %	75 %

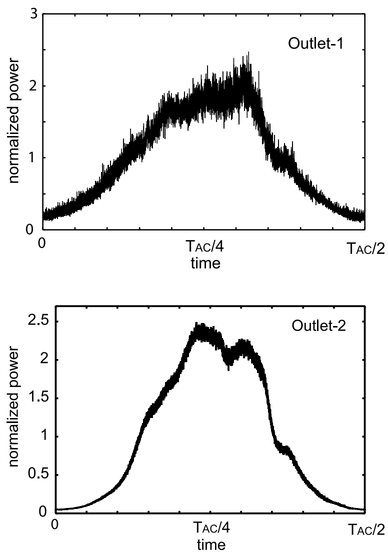

Fig. 11. Cyclic-averaged noise powers at Outlet-1 and Outlet-2.(Case-B)

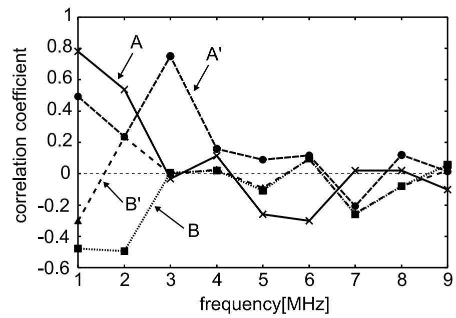

Fig. 12. Correlation coefficient of the instantaneous voltages of the band-pass noise

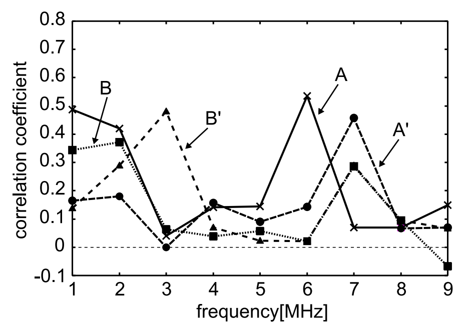

Fig. 13. Correlation coefficient of the instantaneous powers of band-pass noise

The results of the calculation of (4) are listed in Table III. From the table, we can find that the cyclic-averaged powers as time functions for different outlets have large correlation coefficients in almost every case. This may suggest, for example, the possibility of the prediction of the receiver's SNR by a transmitter.

D. Correlations of the instantaneous voltages of band-pass noise

As the behaviors of power-line noise are frequency dependent, this subsection illustrates the correlations of the noise waveforms divided into frequency sub-bands.

First, the samples of wide-band noise components are filtered by a set of nine FIR filters, which have the 1MHz bandwidth centered at 1, 2, 3, ..., 9MHz. As in the previous subsections, the correlation coefficients of noise voltages, noise powers, and cyclic-averaged noise powers are calculated by (1), (2), and (4), for each subband.

The obtained correlation coefficients ρ, ρ_{power} and $\tilde{\rho}$ are shown in Fig.12, Fig.13 and Fig.14. From Fig. 12, it can be observed that the instantaneous noise voltages at a pair of outlets tend to have larger absolute values of correlation coefficient in lower frequency sub-bands. But Fig.13 and 14 does not sustain this conclusion.

V. CONCLUSION

In this manuscript, we discuss the relationships of a pair of noise waveforms measured simultaneously at different outlets in a power-line network. A set of numerical results from the experimental measurements made in a university laboratory is presented. The results in other locations will be presented at the symposium. Though the measurement results are not enough, still we have interesting features of power-line noise: the results indicate that even instantaneous noise voltages at different locations have correlations in a power-line network, especially if the noise waveforms are measured at outlets in a same mains phase. In addition, it is demonstrated that there are large correlations between the noise waveforms at different outlets from the viewpoints of instantaneous and cyclic-averaged noise powers. It is also mentioned that noise waveforms, which are measured simultaneously at different outlets, have frequency dependence on the correlation coeffi-

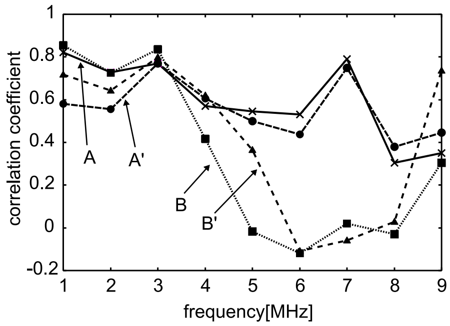

Fig. 14. Correlation coefficient of the cyclic-averaged powers of band-pass noise

cients.

ACKNOWLEDGMENT

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REFERENCES

[1] M. Katayama, T. Yamazato and H. Okada, "Introduction to Robust, Reliable, and High-Speed Power-Line Communication Systems" IEICE Trans.Fundamentals, vol.E84-A, NO12 Dec. 2001.

[2] M. Katayama, T. Yamazato, H. Okada, "A Mathematical Model of Narrowband Power-Line Noise Based on measurements" Proc. of 2005 International Symposium on Power-line Communication and its Applications, pp.152-156 Apr. 2005.

[3] M. Zimmermann and K. Dostert, "Analysis and Modeling of Impulsive Noise in Broad-Band Powerline Communications", IEEE Transaction on Electromagnetic Compatibility,Vol.44,No1, pp.249-258, February. 2002.

[4] Y. Hirayama, H. Okada, T. Yamazato and M. Katayama, "Noise analysis on wide-band PLC with high sampling rate and long observation time", 7th International Symposium on Power-Line Communications and Its Applications, pp.142-147