

# Measurement of Narrowband Channel Characteristics in Single-Phase Three-Wire Indoor Power-Line Channels

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**Abstract**— This manuscript reports the measurement results of narrowband signal propagation of PLC channels. In Japan, in-house wiring is single-phase three-wire, and each branch between an outlet of 100V and the panel board is connected to one of two live conductors and the neutral. Thus a pair of outlets can be classified into three types: connected to different live conductors, connected to the same live conductors by different branches from the panel board, and on the same branch to the same live conductor. It is confirmed that the results of the measurements can be classified by these three types of paths. The results show that frequency responses of narrowband PLC channels are relatively smooth, compared with that of wideband PLC. It is also found that propagation loss in lower frequency range is larger than in higher frequency range. The time independence of narrowband PLC channels are confirmed when no electric appliance is connected to the same live conductor.

**Keywords**— Power-line communication (PLC), signal propagation, indoor wiring, narrowband, single-phase three-wire.

## I. INTRODUCTION

In Japan, the frequency ranges assigned for Power-line communication (PLC) systems are narrowband (10 kHz~450 kHz) and wideband (2 MHz~30 MHz). The latter is suitable for high-speed communications but is allowed only for indoor use because of the concern about interference to other radio services.

In contrast, narrowband PLC systems can be used for both indoor and outdoor. The control of electric appliances, meter readings, and collection of environmental data such as temperature are examples of their prospective applications[1]. Since narrowband still has enough wide bandwidth, which spans more than 400 kHz, medium (a few Mbps) speed short range communications may be another possible application.

In order to design a good PLC system, the knowledge of communication channel is inevitable. In former studies, we have measured and proposed the model of narrow-band noise characteristics[2][3]. There also have been done many researches on the propagation characteristics of power-line channels[4][5]; however, many of them are on wideband, and according to the knowledge of authors, there are not

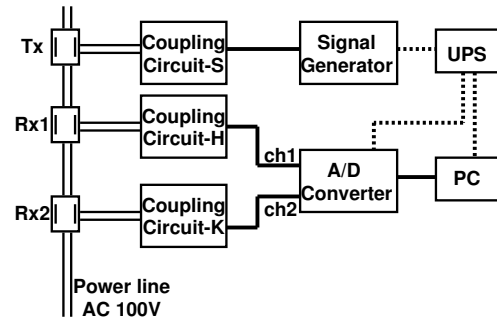


Fig. 1. Measurement System

TABLE I  
MEASUREMENT EQUIPMENT

Component	Maker Model	Model	Specifications
A/D Converter	PAVEC DF-2P2-533	022063198	SPrate:2 Msamples/s Sampling time:1.0 s
Waveform Generator	Agilent 33250A	MY40004839	Output voltage:±4 V
UPS	APC Japan SU700J	NS0043131611	Maximum output capacity:450 W

enough studies on narrowband propagations. Especially, there are not many reports on time varying features of the channel investigated by time continuous measurement. In addition, since in-house wiring is single-phase three-wire in Japan, a pair of outlets is classified into three types. But the systematic measurement of propagations considering the class the communicating outlet-pair is not performed.

This paper reports the measurement results of narrowband signal propagation of PLC channels between a pair of outlets. We measure the propagation characteristics of all possible combinations of outlets in a power-line network where wiring structure and relationship of outlets are clear. The time varying features of propagations is clarified by time-continuous

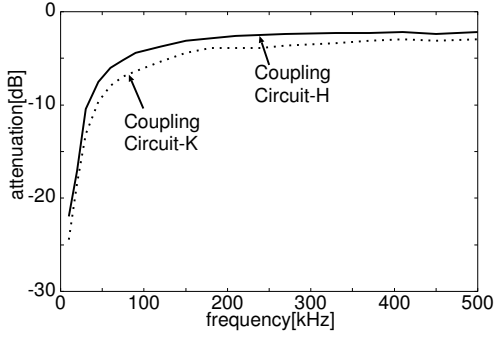


Fig. 2. Frequency response characteristics of Circuit-H and Circuit-K[2]

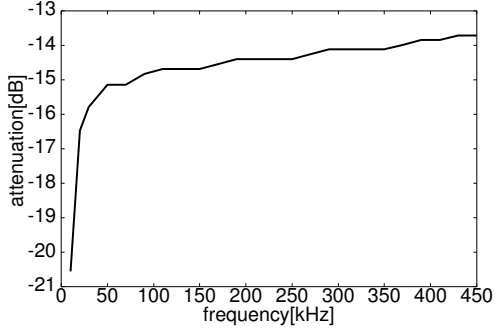


Fig. 3. Frequency response characteristics of Circuit-S

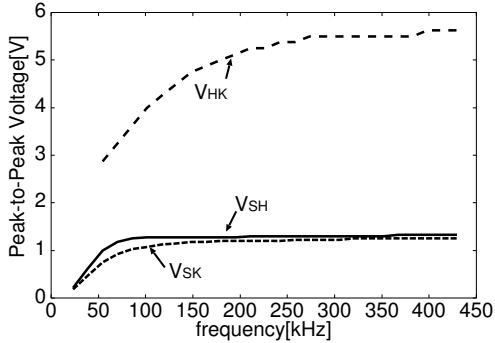


Fig. 4. Frequency response characteristics of combination of Circuits

measurement and it is confirmed that the channel is linear periodically time variant (LPTV) when no electric appliance is connected to the outlets which shares the same live conductor with communicating outlets.

## II. THE MEASUREMENT SYSTEM

### A. Measurement System

Figure 1 shows the measurement system to measure transmission characteristics of PLC channels. This system consists of a function generator, coupling circuits, an A/D converter and a PC. The list of the elements of the system is given in Table I. In this study, measurement is performed under the license of Japanese ministry as a PLC system.

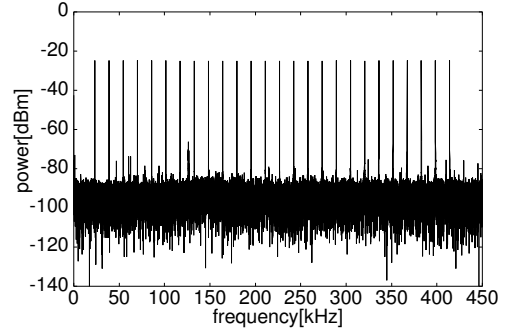


Fig. 5. Power spectrum of sampled at series of Circuit-S and Circuit-H

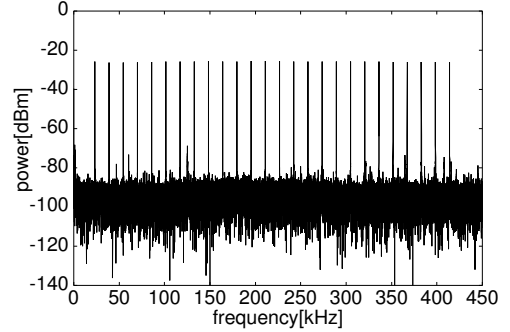


Fig. 6. Power spectrum of sampled at series of Circuit-S and Circuit-K

TABLE II  
TRANSMITTING SIGNAL

Frequency of the lowest carrier $f_0$	23.4375 kHz
Frequency difference $\Delta f$	15.625 kHz
Number of carrier $N$	27
Output voltage	8.0 V
Transmission Power	0.335 W

### B. Coupling Circuit

As shown in Fig. 1, three coupling circuits, Circuit-H, Circuit-K and Circuit-S, are used. Frequency characteristics of Circuit-H and Circuit-K are shown in Fig. 2 and that of Circuit-S is shown in Fig. 3. Figure 4 shows the output voltages of series of each pair of Coupling Circuits when 10 V single-carrier signal is inputted into the Circuits. In Fig. 4,  $V_{SH}$  is the output voltage of the series of Circuit-S and Circuit-H,  $V_{SK}$  is for Circuit-S and Circuit-K, and  $V_{HK}$  is when the two Coupling Circuits are Circuit-H and Circuit-K. Circuit-S is used on the transmitting side and Circuit-H and Circuit-K are used on the receiving sides.

### C. Transmitting Signal

In order to clarify the time variation of the propagation, multi-carrier signal is used, which can be expressed as

$$\sum_{n=0}^{N-1} V_n \cos 2\pi[(f_0 + n\Delta f)t + \theta_n] \quad (n = 0, 1, \dots, N-1) \quad (1)$$

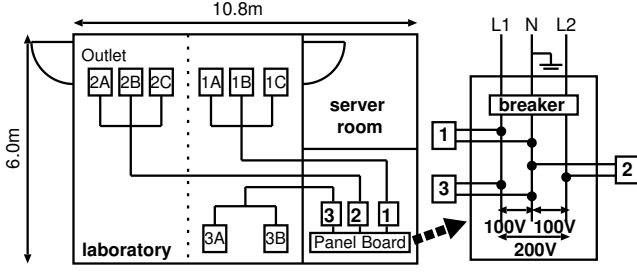


Fig. 7. Cabling structure

TABLE III  
COMBINATION OF TWO OUTLETS(28 PATHS)

same-branch	different-branch		
	in-phase	cross-phase	
1A-1B	3A-1A	1A-2A	3A-2A
1A-1C	3A-1B	1A-2B	3A-2B
1B-1C	3A-1C	1A-2C	3A-2C
2A-2B	3B-1A	1B-2A	3B-2A
2A-2C	3B-1B	1B-2B	3B-2B
2B-2C	3B-1C	1B-2C	3B-2C
3A-3B		1C-2A	
		1C-2B	
		1C-2C	

where  $N$  is the number of carriers,  $f_0$  is the frequency of the lowest carrier and  $\Delta f$  is the frequency difference between adjacent carriers. The amplitude of each carrier  $V_n$  is calibrated to compensate the frequency characteristics of Circuits. Phase of each carrier  $\theta_n$  is determined to reduce the PAPR (Peak-to-average Power Ratio). Then the transmitted power of this signal is

$$P = \frac{1}{2R} \sum_{n=0}^{N-1} V_n^2, \quad (n = 0, 1, \dots, N-1) \quad (2)$$

where  $R$  is the impedance of the power-line. Parameters used in measurements are shown in Table II. Figure 5 shows the output power spectrum measured at the output of the series of Circuit-S and Circuit-H when 10 V multi-carrier signal is inputted. Figure 6 shows the output power spectrum after the signal is passed to Circuit-S and Circuit-K.

#### D. Processing Method of Receiving Signal

When the sampling is performed every  $\delta$  s over the duration  $T$  s, A/D converter stores  $T/\delta$  samples for ch1 and ch2, which denoted as  $s^{(1)}[i]$  and  $s^{(2)}[i]$ . In this study,  $T$  is 1 s and  $\delta$  is  $0.5 \mu s$ . DFT (Discrete Fourier Transform) is performed on the received signal and filtered to cut the frequency and IDFT (Inverse Discrete Fourier Transform) is performed. Characteristic of received signal in frequency domain can be expressed as

$$S_k^{(c)} = \frac{1}{N_{DFT}} \sum_{i=0}^{N_{DFT}-1} s[i]^{(c)} \exp\left(-j \frac{2\pi}{N_{DFT}} ki\right) \quad (3)$$

( $c = 1, 2; k = 0, 1, 2, \dots, N_{DFT} - 1; i = 0, 1, 2, \dots, N_{DFT} - 1$ )

TABLE IV  
MEASUREMENT CONDITIONS

Path	Electrical appliance	Location of appliance
same-branch (1A-1B) different-branch of in-phase (1A-3A) cross-phase (1A-2A)	nothing	nothing
same-branch (2A-2B)	TV NEC (C-20R33)	2A 2B 2C 3A

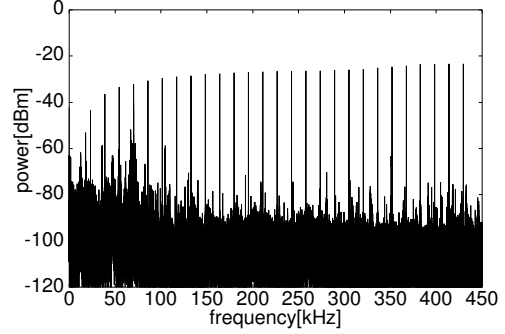


Fig. 8. Power spectrum of signal with noise at Outlet1B

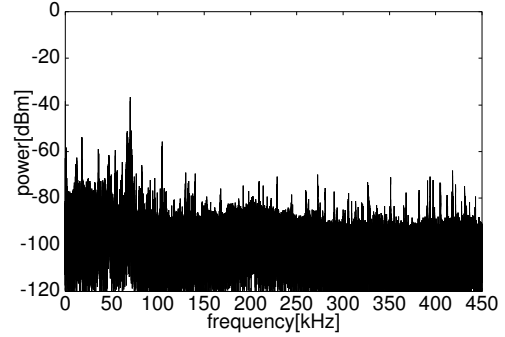


Fig. 9. Power spectrum of noise at Outlet1B

where  $S_k^{(c)}$  is the  $k$ th Fourier coefficient of  $s[i]^{(c)}$ , the samples of  $c$ th channel, and  $N_{DFT}$  is the window size which is  $2^{20}=1048576$ . In order to set the frequency of each multi-carrier signal  $f_c$  in the center of the bandwidth  $\Delta$ , we define  $f_c = f_0 + k\Delta$  and  $\Delta = \Delta f$ , for  $k = 0, 1, \dots, N-1$ . Signal attenuation is given by

$$10 \log_{10} \frac{\overline{V_{nr}^2}}{\overline{V_{ns}^2}} \quad (n = 0, 1, \dots, N-1) \quad (4)$$

where  $V_{ns}$  is VRMS (volts root-mean-square) of each carrier received at receiving point and  $V_{nr}$  is  $V_{RMS}$  of each carrier passed through series of two Coupling Circuits.  $V_{ns}$  and  $V_{nr}$  are averaged taken over 1600 samples.

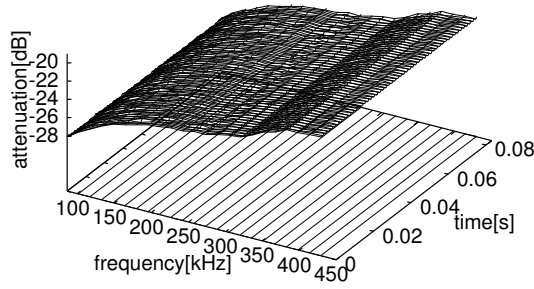


Fig. 10. Propagation loss between Outlets1A-1B (the same branch)

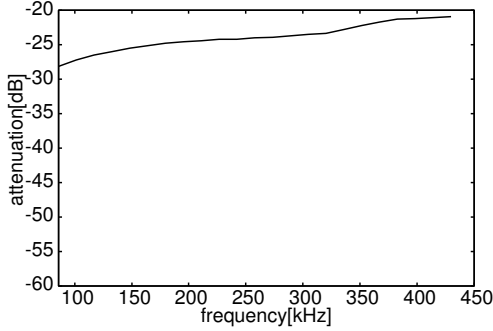


Fig. 11. Time averaged propagation loss between Outlets1A-1B (the same branch)

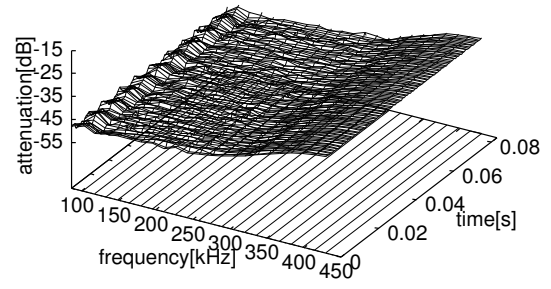


Fig. 12. Propagation loss between Outlets1A-3A (different branch, the same-phase)

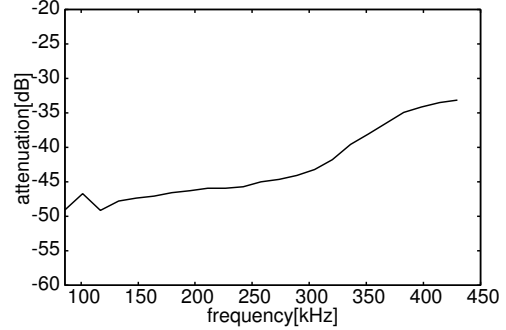


Fig. 13. Time averaged propagation loss between Outlets1A-3A (different branch, the same-phase)

### III. MEASUREMENT OF INDOOR POWER LINE NETWORK

The measurements are performed at a room of a ten-storied building of Nagoya University shown in Fig. 7. In this building, in-house wiring is of single-phase three-wire, and each branch between an outlet of 100 V and the panel board is connected to one of two live conductors (L1 or L2) and the neutral (N). Thus a pair of outlets can be classified into three types as shown in Table III: on the same-branch, on the different-branches but connected to the same live conductor (in-phase) and a pair connected to different live conductors (cross-phase). Signal propagation of these three types of path is measured and compared. First, under the condition that only the Coupling Circuits of measurement systems are connected to the outlets, all paths are measured (seven paths of the same-branch, six paths of the different-branch of in-phase and fifteen paths of the cross-phase.) Second, an electric appliance is also connected to an outlet in addition to the Coupling Circuits to confirm the influence of the appliance is clarified. Measurement conditions are listed in Table IV.

#### A. Results of Transmission Characteristics

Figure 8 shows the power spectrum of received signal at Outlet1B when signal is inputted at an outlet on the same branch, i.e., Outlet1A. Figure 9 shows the power spectrum of Outlet1B when no signal is inputted. Comparing these figures, the power of the signal is 5 dB above the floor noise in the frequency range 85.9375 kHz to 429.6875 kHz. Thus, signal propagation is calculated in this frequency range (i.e.,  $f_c =$

$f_0 + j\Delta$  for  $j = 5, 6, \dots, N-1$ ) as shown in Figs. 10 and 11, where Fig. 11 is time average of Fig. 10. Lines in Fig. 10 represent the frequencies of carriers. In the same way, signal propagation between outlets on different branches of in-phase i.e., Outlets1A and 3A is shown in Figs. 12 and 13. For the cross-phase pair of Outlets1A and 2A, propagation is calculated in the frequency range where signal is more than 5 dB above the noise level ( $f_c = f_0 + j\Delta$ ;  $j = 6, 7, \dots, N-1$ ) as shown in Figs. 14 and 15.

Figures 10-15 show that signal propagation loss between outlets on the same-branch has the smallest attenuation, and that the path of the cross-phase has the largest attenuation.

In time domain, it is known that the signal propagation shows LPTV features synchronous to the absolute value of the mains AC voltage in the wideband PLC systems[5]. In contrast, as shown in Figs. 10, 12 and 14, the signal propagations of the narrowband PLC channels are almost time-invariant.

In frequency domain, as shown in Figs. 10-15, it is also noteworthy that signal propagation depends on the frequency and has larger attenuation as the frequency become low. This result does not agree with that of the former studies, where power-lines are expressed as distributed constant circuit which has larger attenuation in higher frequencies. The authors are now exploring the cause of the drop in lower frequencies. One possible reason is the influence of main circuit breaker at the panel board.

Many past studies have reported that the signal propagation

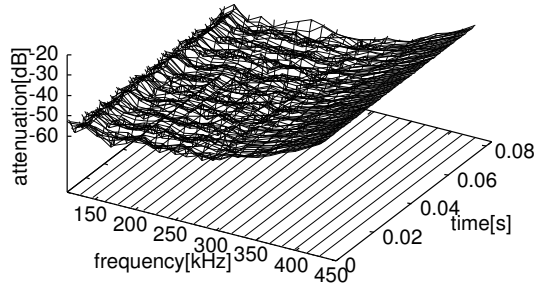


Fig. 14. Propagation loss between Outlets1A-2A (cross-phase)

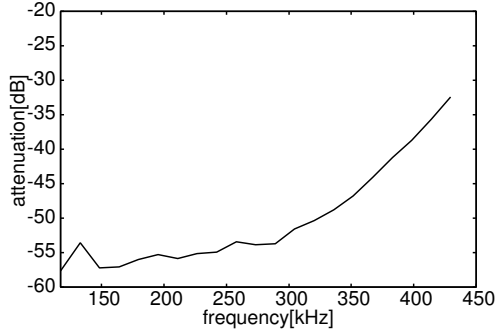


Fig. 15. Time averaged propagation loss between Outlets1A-2A (cross-phase)

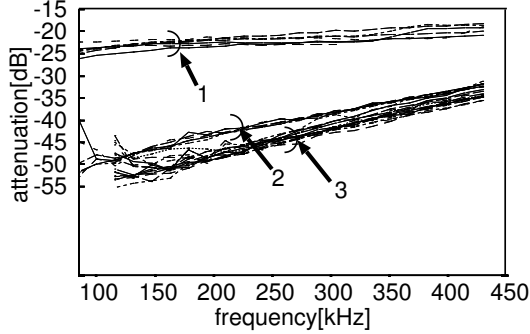


Fig. 16. Propagation loss of 28 paths

in wideband has frequency notches caused by multipath. On the contrary, our result shows that the signal propagation is smooth in the narrowband. This is because the wavelength of the narrowband is in the range several hundreds m to 30 km, and thus the phase difference between direct wave and reflected wave is small in the indoor power-lines.

Figure 16 shows the signal propagations of all paths listed in Table III. From this figure, it is confirmed again that signal propagation of the cross-phase paths have the largest attenuation and the same-branch paths have the smallest attenuation. It is also confirmed in all cases that the signal propagations depend on the frequency and have larger attenuation in low frequency range.

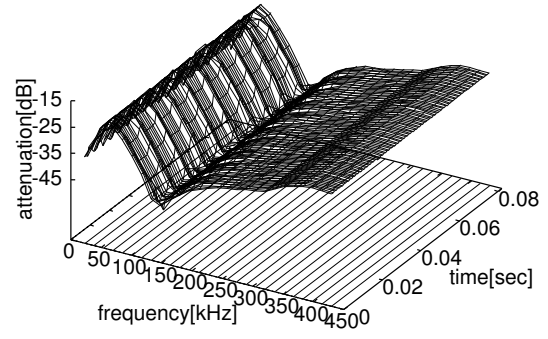


Fig. 17. Propagation loss between Outlets2A-2B with TV connected at 2A

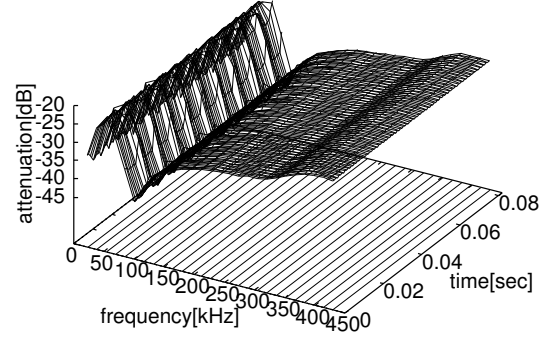


Fig. 18. Propagation loss between Outlets2A-2B with TV connected at 2B

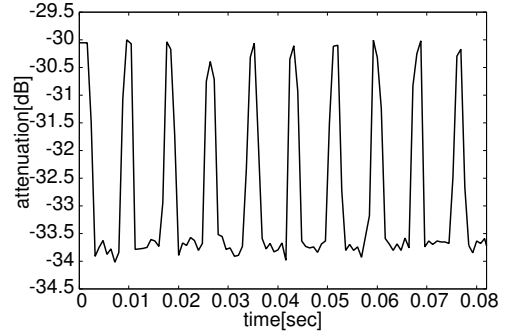


Fig. 19. Time variation of propagation loss between Outlets2A-2B with TV connected at 2A at  $f=101.5625$  kHz

### B. The Influence of Electric Appliance on the Transmission Characteristic

It is known that periodic variation of signal propagation is caused by time-variant behavior of electric appliances synchronous to the mains frequency in wideband systems[5]. In order to confirm the influence of electric appliances in narrowband, we connect a TV(as an example of an electric appliance with voltage synchronous impedance change) to the outlets of the power-lines. In this series of experiments the transmitting point is Outlet2A and the receiving point is Outlet2B.

Signal propagation when TV is connected to the transmitting point is shown in Fig. 17 and signal propagation when TV is connected to the receiving point is shown in Fig. 18.

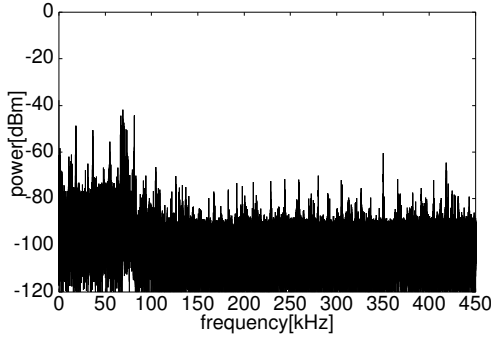


Fig. 20. Power spectrum of noise at Outlet2B with TV connected at 2A

Comparing Fig. 17 and Fig. 18 to Fig. 10, we can notice that signal is attenuated at 150 kHz. It is caused by noise filter of the electric appliance. In Fig. 17 and Fig. 18, time variation is observed but only in the range 100 kHz to 150 kHz. Time variation of signal propagation between Outlets2A-2B with TV connected at 2A at 101.5625 kHz is shown in Fig. 19. It is found that signal propagation of the narrowband also vary synchronous to the mains frequency (60 Hz) but only at particular frequencies. Figure 20 shows the power spectrum of noise at Outlet2B with TV connected at 2A. Comparing Fig. 19 to Fig. 20, it is clear that the variation of signal propagation is not due to that of noise.

Figure 21 shows the signal propagation when the TV is connected to Outlet2C (the same-branch). Also in this case, time variation and attenuation in the frequency exist, but the attenuation is small. Figure 22 shows the signal propagation when the TV is connected to Outlet3A (at the different-branch of in-phase). In this case, the influence of the appliance is same all and propagation is almost same as that of Fig. 10 when no appliance is on power-line.

From above discussion, it can be deduced that signal propagation of power-line is influenced not only by topology of power-lines, but also by electric appliances connected to the outlets.

#### IV. CONCLUSIONS

The narrowband signal propagation of indoor power-lines is measured. The results show that the signal propagation of the cross-phase paths have the largest attenuation while that of the same-branch paths have the smallest attenuation. It is found that the signal propagation in narrowband depends on the frequency and has larger attenuation in low frequency region. In contrast to wideband PLC channels whose frequency response is characterized by multipath, the cause of notches or attenuations in frequency domain of narrowband PLC channels is appliances (including circuit breakers) connected to the lines. Time variation is not shown when no electric appliance is connected to outlets, and when an electric appliance is connected to outlets, time variation can be found but in some particular frequency range. It is concluded that signal propagation of the narrowband is smooth in the frequency

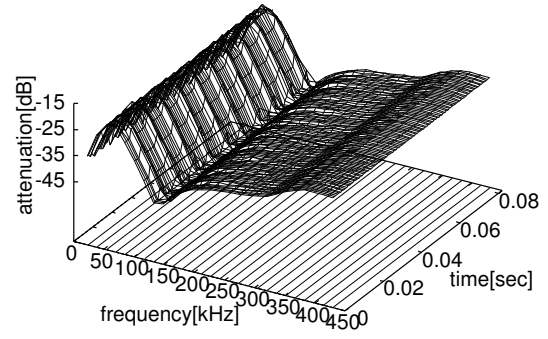


Fig. 21. Propagation loss between Outlets2A-2B with TV connected at 2C

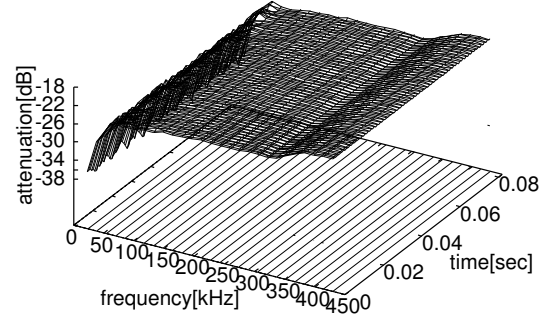


Fig. 22. Propagation loss between Outlets2A-2B with TV connected at 3A

domain and has little time variation, so that communication system may become simpler than that for the wideband. However, when an electric appliance is connected to outlet, adaptation to the time variant feature may be worth to consider.

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#### REFERENCES

- [1] Y.Chen, et al., "A Reliable Energy Information System for Promoting Voluntary Energy Conservation Benefits," IEEE Journal on Selected Areas In Communications. Vol.21,No.1,pp.102-107, January 2006.
- [2] A.Kawaguchi, et al., "Correlations of Noise Waveforms at Different Outlets in a Power-line Network," IEEE International Symposium on Power Line Communications and its Applications,pp.92-97,Orland,America,March.2006.
- [3] M.Katayama, et al., "A Mathematical Model of Noise in Narrowband Power Line Communication Systems," IEEE Journal on Selected Areas In Communications. Vol.24,No.7,pp.1267-1276, July 2006.
- [4] M.Zimmermann, et al., "A Multipath Modeling for the Power line Channel," IEEE Journal on Selected Areas In Communications. Vol.50,No.4,pp.553-559, April 2002.
- [5] F.J.Canete, et al., "Analysis of the Cyclic Short-Term Variation of Indoor Power Line Channels," IEEE Journal on Selected Areas In Communications. Vol.24,No.7,pp.1327-1338, July 2006.