# Wideband Channel Measurements and Modeling for In-House Power Line Communication

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**ABSTRACT**

This paper reports the results of extensive wideband channel measurements conducted on in-house outlets at 10~30MHz. Two kinds of measurements were performed: impulse response measurements and noise measurements. Impulse responses were obtained in two different time scales: 50 impulse responses taken for 1 minute to see short term variation and for 6 milliseconds to see very short term variation. Noise measurements were carried out to measure background noise, appliance noise and periodic noise. These measurements at a specific outlet are repeated in every other hour over 24 hours. The measured data were carefully reduced and analyzed to extract relevant information to obtain time-varying channel and noise characteristic for in-house power line communication.

## I. Introduction

In-house power line has recently been considered as an alternative medium for high speed data transmission for applications like home networking and Internet access. Representative channel parameters such as noise, signal attenuation, distortion, time-varying properties and input impedance at outlets play an important role to determine the performance of power line communication. Many articles regarding power line communication channel characterization at a frequency band from 1KHz to 500KHz were reported in the literature. However, this frequency band is estimated inadequate for high data rate communications [1-2]. Some papers surveyed the channel properties in higher frequencies channel [3-5]. But, only few articles described multi-path and time-varying nature of power line communication.

This paper presents the results of extensive measurements to characterize the wideband channel properties at the frequency band from 10MHz to 30MHz and the noise characteristic at the frequency band from 1MHz to 40MHz for in-house power line communication. Impulse responses and noise characteristic for home networking using power line are obtained from the measured data. The careful analysis of measured results was made to give path loss, mean excess delay, RMS delay spread, background noise, appliance noise and periodic noise at each outlet. Based on the obtained parameters, we proposed statistical multipath channel model and noise characteristic in wide frequency band.

Section II describes the measurement system for the impulse response and noise characteristic. Section III presents the measured impulse responses and noise properties. Finally, the conclusions are given in section IV.

## II. Measurements

The measurements were carried out by the pseudo-noise (PN) correlation method to obtain channel impulse responses. Fig. 1 illustrates the channel sounding measurement system [6]. PN Generator was realized by FPGA board. PN sequences generated with the chip rate of 20MHz are multiplied by the carrier frequency of 21MHz. The carrier signal modulated by PN sequences are amplified by power amplifier and injected into the power line by coupler. In order to achieve the high sensitivity of the receiver system, a low noise amplifier (LNA) is inserted after the coupler of the receiver. The received signal after BPF is over-sampled by Digital Oscilloscope (DO) or analog to digital converter (ADC) and sampled data are saved by PC. After completing measurement process, over sampled signals are down converted and cross-correlated with the PN sequences on PC to give channel impulse responses.

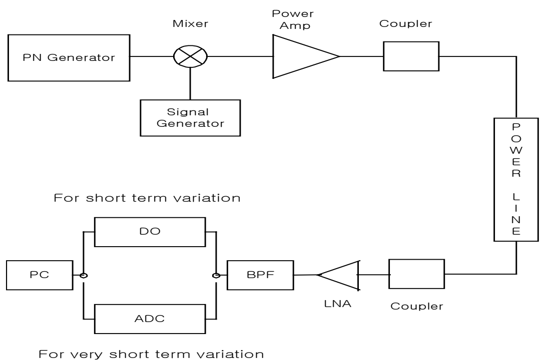



Fig. 1 Block diagram of power line channel impulse response measurement system

The measurement system can resolve the pulse duration of 50ns which is the time resolution of the auto correlation of 20MHz PN sequences. Measurements were performed in two different time scales. For the measurements of the first time scale measurements, 50 power delay profiles (PDPs) were taken for 86 seconds to see the short term variation of the channel. For the second time scale, 31 PDPs were taken for 6.3475 milliseconds to see the very short term variation. Digital Oscilloscope was used in measurements for the short term variation and the analog to digital converter card with 8M on-board-memory was used for the very short term variation.

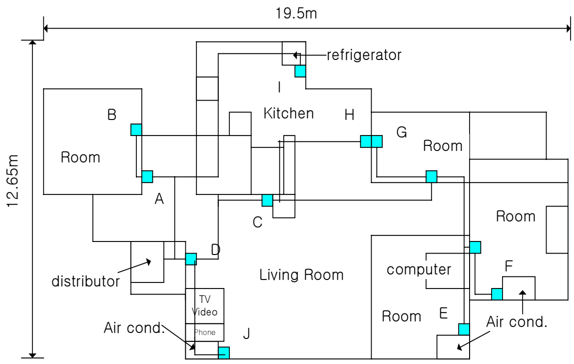



Fig. 2 floor of measurement environment

Fig. 2 shows the floor plan of the residential house in which the measurement campaign was conducted. The transmitter was fixed at outlet A as shown in Fig. 2, and the receiver were located at scattered outlets except outlet A (outlet B-J) sequentially according to the order of measurements. Short term or very short term variation measurements were repeated at every other hour over 24 hours in the summer(Aug.30.2001) and the fall(Oct.30.2001). In case of measurements from 3 a.m. to 6 a.m., electric appliances such as PCs, television, air conditioner except refrigerator were switched off. For the rest of measurements, all electric appliances were turned on. Calibration measurements of the system were taken by inserting only a step attenuator between the couplers for the transmitter and the receiver.

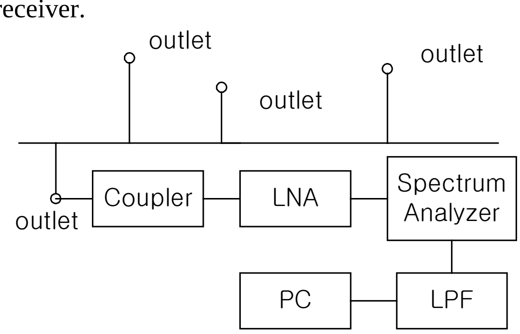


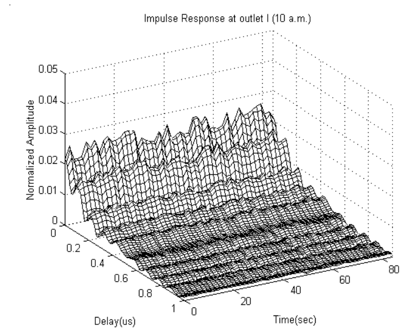

Fig. 3 Block diagram of noise measurement system

The noise measurement system is composed of receiving coupler, LNA, low pass filter, spectrum analyzer and PC as shown in Fig. 3. As impulse response measurements, noise measurements at each outlet were repeated at every other hour over 24 hours. The spectrum analyzer was swept over the frequency band from 1MHz to 41MHz. The sweep time of spectrum analyzer over the measurement frequency band was 2 seconds and data were taken at 401 sampling frequencies over the swept band. At each measurement location of noise measurement 50 snap shots were taken for a minute and taken an average mode measurement of 50 sweeps are followed.

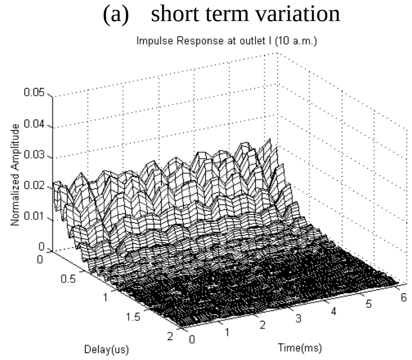
## III. Results

### *A. Channel sounding results*

Fig. 4(a) and (b) show measured impulse responses for the short term variation and the very short term variation respectively for the receiver location of outlet I at 10 a.m.. From these graphs, we can tell the significant difference between the short term variation and the very short term variation of the channel. The amplitudes of the 1st path in Fig. 4(b) show periodic variations with order of time in milliseconds, while periodic variations are observed not to be distinct in Fig. 4(a). Fig. 5 illustrates that the amplitudes of the 1st path at outlet D, G and E for the very short term variation measurement fluctuate periodically. It is conjectured that this periodic fluctuation is caused by the periodic noise source that might exist in power line.




(a) short term variation




(b) very short term variation

Fig. 4 Impulse response at outlet I for short variation and very short variation

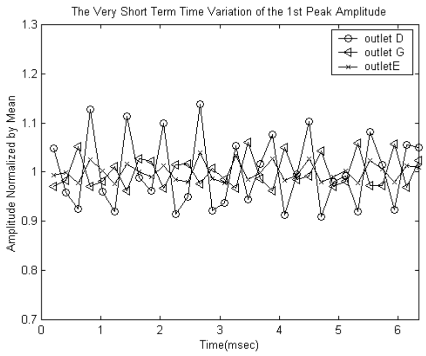



Fig. 5 Amplitude variation of first path for very short term variation at outlet D,G and E

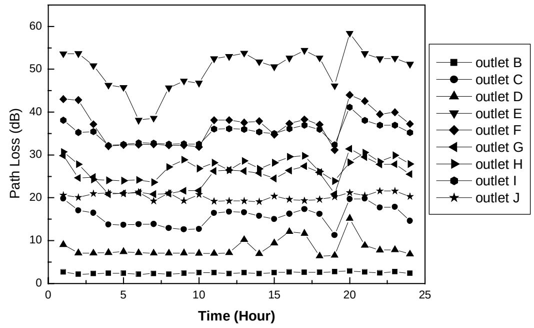



Fig. 6 Time variation of attenuation at each outlet over 24-hour

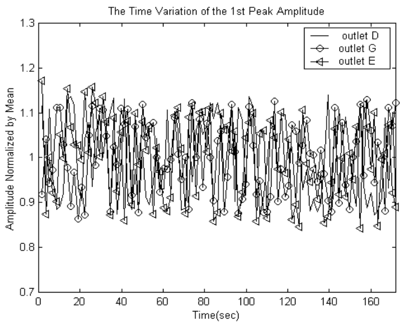
Table 1. Average attenuation of the 1st path( $1^{st}\ P_{atten}\ (dB)$ ), Mean Excess Delay $\bar{\tau}(\mu s)$ , $\tau_{\max}(\mu s)$ , a average of RMS Delay Spread $\bar{\sigma}(\mu s)$ , $\sigma_{\max}(\mu s)$ and average attenuation of the 2nd Path( $2^{nd} P_{atten}(dB)$ ) at each outlet

| Outlet | $1^{st} P_{atten}(dB)$ | $\bar{\tau}(\mu s)$ | $\tau_{\max}(\mu s)$ | $\bar{\sigma}(\mu s)$ | $\sigma_{\max}(\mu s)$ | $2^{nd} P_{atten}(dB)$ |
|---|---|---|---|---|---|---|
| B | -2.457 | 0.22 | 0.44 | 1.73 | 2.17 | -12.86 |
| C | -15.747 | 0.20 | 0.39 | 1.59 | 2.1 | -28.02 |
| D | -8.217 | 0.22 | 0.46 | 1.61 | 2.45 | -17.24 |
| E | -50.103 | 1.00 | 2.26 | 4.41 | 6.18 | -53.49 |
| F | -36.756 | 0.43 | 0.78 | 2.62 | 3.62 | -42.85 |
| G | -24.972 | 0.39 | 0.76 | 2.68 | 3.48 | -36.19 |
| H | -27.252 | 0.30 | 0.71 | 2.49 | 3.60 | -38.44 |
| I | -35.198 | 0.81 | 1.03 | 3.95 | 5.52 | -39.27 |
| J | -20.271 | 0.47 | 0.63 | 2.72 | 3.17 | -25.32 |

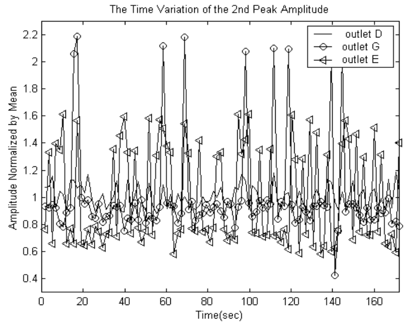
Fig. 6 shows the change of path loss with time over 24 hour at each outlet. Between 3 a.m. and 6 a.m., the attenuation at each outlet was decreased by 10-20dB depending on receiver locations. For example, the attenuation at outlet E shows the maximum decrease of 20dB, while at outlet B minimum decrease of 1dB. Except the extreme cases at those two locations, attenuations for all the other outlets are normally decreased by about 10dB. It is presumed that the decrease in attenuation between 3 a.m. and 6 a.m. is caused by the fact that electric appliances were turned off during these time intervals. Noise effect of electric appliances was discussed at section III-(b).

Table 1 summarizes the impulse response measurements to give the time averaged power line channel parameters such as attenuation of the 1st path, mean excess delay, RMS delay spread and attenuation of the 2nd path. Seen in Fig. 6, received signals at outlet F and I suffer almost the same amount of attenuation over 24-hour although distance between the outlet A (Tx location) and F is different from that between the outlet A and I. Table 1 reveals that each distance between outlet A (Tx location) and receiver outlets E and F is almost equal but the mean excess delay and RMS delay spread are so different each other. As a result it is found that the distance between the transmitter and receiver is not the dominant factor to determine channel parameters; rather, it is inferred that in-house power line channel is influenced by number of junctions and impedance matching condition at branch and endpoints [6,7].

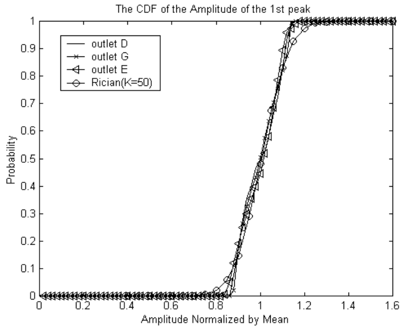
The average parameters obtained from in-house power line measurements are as follows: average 1st path attenuation of 24.55dB, mean excess delay of 0.45 $\mu s$, RMS delay spread of 2.64 $\mu s$ and average 2nd path attenuation of 32.63dB. The statistical properties of the amplitude at each path are obtained from measured impulse responses. The amplitude variations of the 1st and 2nd path obtained from short term variation measurements at outlet D, G, E are shown in Fig.7. The cumulative distribution functions (CDFs) of the first path signals were found to fit a Rician distribution. Some CDFs of the second path signals were found to fit a Rician distribution at outlet D, G. The remaining outlets are off from the Rician distribution and the CDFs of these were found to be flat distribution near mean value. The analysis reveals that the statistics of the amplitudes normalized by the time averaged value follows the Rician distribution with unit mean and K factor of 50 for the first path while unit mean and K factor of 10 for the second path. On the other hands, the phase of each path signals are found to be uniformly distributed from 0 to 2π.



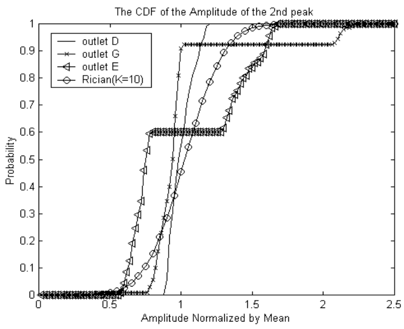

(a) The time variation of the 1st peak amplitude




(b) The time variation of the 2nd peak amplitude




(c) The CDF of the amplitude of the 1st peak




(d) The CDF of the amplitude of 2nd peak

Fig.7 Amplitude variation of each path for short duration and the CDF of the each path amplitude

*B. Noise Measurements Results*

Noise on power line channel is classified into three categories: background noise, appliance noise, and periodic noise. Background noise and appliance noise is measured in wide frequency band. And periodic noise is measured in narrow frequency band.

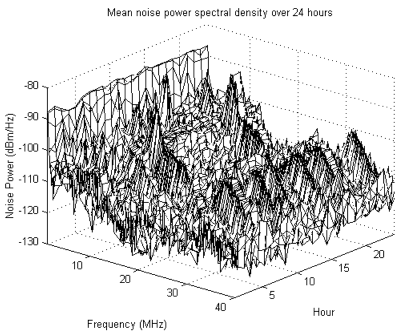
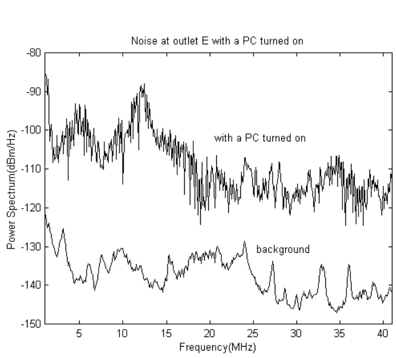


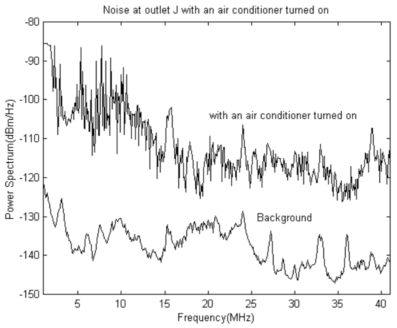

Fig.8 24 hour noise results at outlet E

Fig. 8 shows mean power spectral density of noise as a function of time over 24-hours at outlet E. The change in mean power spectral density of total instantaneous noise between during daytime and during other times is observed to be about 15dB. This change can be explained by the fact that most of electric appliances except a refrigerator are turned off during night time between 3 a.m. to 6 a.m.. As shown in Fig. 6, time dependency of 1st path attenuation at each outlet during day time is believed to be relative to electrical appliance noise.

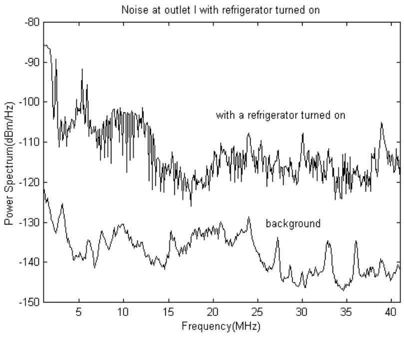
Fig. 9 shows that noises due to variety of appliances are observed at outlets connected with appliances such as PC, air conditioner, refrigerator and TV. In addition to these appliance noises, background noises which were observed at any time over the entire frequency band with all appliances turned off are presented to be compared with each appliance noise. The averaged difference over the swept frequency between background noise and aggregated noise with appliances turned on at each outlet is found to be 49dB at outlet E with PC, 45.5dB at outlet J with air conditional, 45dB at outlet I with refrigerator and 47dB at outlet D with TV, from 1MHz to 41MHz.



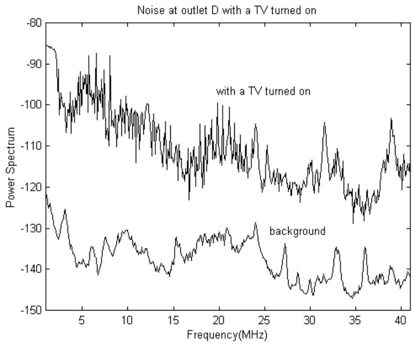

(a) Noise at outlet E with a PC turned on




(b) Noise at outlet J with air conditioner turned on




(c) Noise at outlet I with refrigerator turned on




(d) Noise at outlet D with TV turned on

Fig. 9 Appliance noise with PC, air conditioner, refrigerator and TV

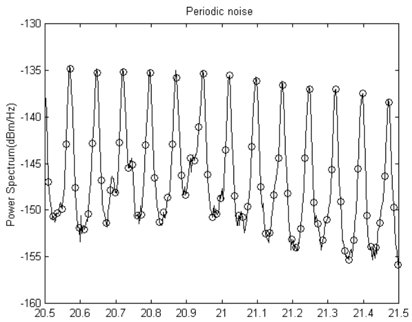



Fig.10 Periodic noise at narrow frequency band

Fig. 10 represents the variation of the aggregated noise with frequency, which was measured at 21MHz inside a test house. In this measurement, span frequency is 1MHz and frequency interval between data points with a mark of circle is 12.5 Hz. However there exist time difference of 2.5ms between each sampling frequency. As a result, time interval between adjacent peaks of noise is turned out to be 15 ms, which is equivalent to 62.5Hz in frequency. From this observation it is assumed that wideband noise which is independent of frequency but fluctuate with time, period is corresponding to the frequency of power transmission in Korea existed in power line.

## IV. **Conclusions**

In this paper, the communication channel properties of in-house power line are characterized through impulse response measurements and noise measurements. We obtained channel parameter such as attenuation, mean excess delay and RMS delay spread from the measured. The attenuation of each outlet was influenced by noise induced by electric appliances and was not related to the distance of outlets. The statistics of the amplitude normalized by the time averaged value at each path follow the Rician (K=50 for $1^{st}$ path amplitude or K = 10 for $2^{nd}$ path amplitude) distribution curve. The amplitudes of the $1^{st}$ path for very short term variation is periodic. And noise characteristic of power line channel such as background noise, appliance noise and periodic noise are studied.

## References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