

## Channel Measurements and Modelling for Indoor Power Line Communications

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### Abstract

*In order to obtain power line communications channel transmission characteristics, impulse responses measurements were performed on the basis of PN sequence's excellent periodic autocorrelation properties. Meanwhile, a compensation method in frequency domain was proposed to improve the measurement precision. Then, the empirical multipath channel model of power line is presented from the measured results. The simulation and experimental measurement results not only have verified the efficiency of the proposed model, but also showed that the measurement method has fast, simple and convenient characteristic. Finally, the statistical characteristics of path amplitude and the delay spread are obtained through the analysis of measured results.*

**Keywords:** power line communications (PLC), PN sequence, impulse responses

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### 1. Introduction

As an effective access technology, the realization of high rate communication over low-voltage power line has become a hot research topic [1-3]. Because using the existing power cable infrastructure for communication purposes, it has notable features such as no cabling, low cost, plug and play, a wide range of coverage, convenient connections, etc [4, 5]. However, unlike the other wired communication mediums, the power lines were suited to convey electrical power [6, 7], not information. The transmission of high frequency signals in power lines may introduce more disadvantages [8-10]. Therefore, measuring and understanding of the power line channel characteristics become vital.

The channel impulse response is very important characteristics in PLC. From the impulse response, the complex transfer function and channel characteristics can be obtained using the Fourier transform. Meanwhile, channel impulse response gives an indication if and how complex an equalizer is needed for reliable communication.

Reference [11] and Reference [12] obtained channel impulse responses by modulated periodic PN sequence. In order to obtain reliable amplitude and phase frequency response characteristics, the complicated process for modulation, demodulation and synchronization have to be performed. These cause the measurement of power line communications channel transmission characteristics to become complicated. The measurements were carried out by PN correlation method to obtain channel impulse responses in Reference [13]. However, the measurement method did not involve any synchronous measurement. So the reliable phase frequency response characteristics can not be acquired.

To overcome these disadvantages, this paper presents a method of measuring the indoor PLC channel impulse responses. It bases on PN sequence's excellent periodic autocorrelation properties with synchronous and asynchronous measurement method respectively. From the measured impulse response, the empirical multipath channel model of power line is proposed and the channel transmission characteristics are obtained. Meanwhile, multipath parameters, such as time delays and the statistical characteristics of path amplitude, are analyzed.

## 2. Measurements

### 2.1. Measurement Method

PN sequences are easily generated using linear feedback shift registers, and they possess excellent periodic autocorrelation properties, as illustrated in Figure 1. Therefore, periodic PN sequence is used as the test signal. In Figure 1,  $r_i(\tau)$  is normalization periodic autocorrelation function of PN sequences,  $\tau$  is the time delay,  $T_c$  denotes the chip rate (clock period),  $N$  defines the length of PN sequences and  $N=2^n-1$ ,  $n$  is the number of the linear feedback shift registers.  $NT_c$  is the period of PN sequences.

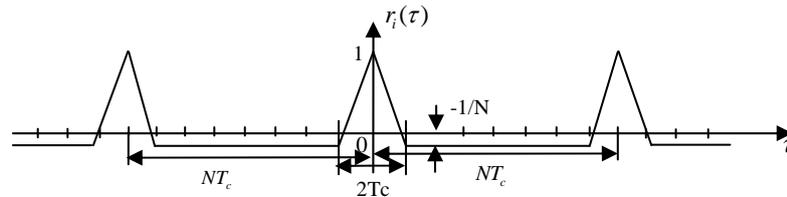


Figure 1. Normalization Periodic Autocorrelation Function of PN Sequences

Figure 2 illustrates the channel sounding measurement system. PN generator was realized by Agilent signal generator. PN sequence generated with the chip rate of 20MHz and injected into the power line by coupler. The received signal is over-sampled at the rate of 100MS/s by digital oscilloscope and sampled data are saved by PC. After completing measurement process, over sampled signals cross-correlated with the reference PN sequence on PC to give channel impulse responses. The resolution of the measured impulse response is  $0.05\mu s$  that is same as the chip duration of PN sequence and is not better than  $0.05\mu s$ .

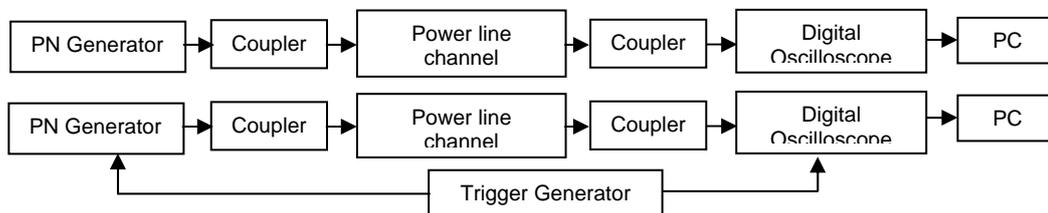


Figure 2. Block Diagram of the Power Line Channel Measurement System, Non-synchronous Measurement System (upper), Synchronous Measurement System (lower)

In Figure 2, there is not need synchronization between receiver and transmitter in non-synchronous measurement system, so there can be a long distance between the test ports of PN generator and digital oscilloscope. However, from the measured data only the reliable amplitude frequency response characteristics can be obtained using the Fourier transform. In Figure 2 synchronous measurement system, receiver and transmitter are synchronized and there can not be a long distance between the test ports of the measurement system. However, the reliable amplitude and phase frequency response characteristics can be obtained.

### 2.2. Measurement Principle

In order to measuring the linear characteristics of PLC channel, the measurement principle is derived. From the sounding of mobile radio channels, a linear system can be described by its impulse response  $h(t, \tau)$ . It is assumed that during the short measurement period  $h(t, \tau)$  is time invariant, such that  $h(t, \tau) = h(\tau)$ . If white noise  $n(t)$  is applied to the

input of a linear system with impulse response of  $h(t)$ , the output signal  $w(t)$  is the convolution of  $n(t)$  and  $h(t)$ :

$$w(t) = \int h(\tau)n(t-\tau)d\tau \quad (1)$$

If the output signal  $w(t)$  is cross-correlated with a delay replica of the input  $n(t-\tau)$ , then the resulting cross-correlation coefficient is proportional to the impulse response of the system  $h(\tau)$ , evaluated at the delay time. This can be shown as follows:

$$E[w(t)n^*(t-\tau)] = E[\int h(\zeta)n(t-\zeta)]n^*(t-\tau)d\zeta] = \int h(\zeta)R_n(\tau-\zeta)d\zeta \quad (2)$$

where  $R_n(\tau)$  is the autocorrelation function of white noise  $n(\tau)$ , which is equal to the single-sided noise power spectral density,  $N_0$ . Hence, Eq. (2) can be expressed as:

$$E[w(t)n^*(t-\tau)] = N_0h(\tau) \quad (3)$$

Therefore, the impulse response of a linear system can be evaluated using white noise, and some method of correlation processing. In practice, it is unrealistic to generate white noise, and PN sequence is used instead of the white noise due to its noise-like characteristic.

Let  $x(n)$  be PN sequence, transmit function is  $h(n)$ ,  $y(n)$  denotes the received signal, therefore

$$y(n) = x(n) \otimes h(n) \quad (4)$$

where  $\otimes$  denotes convolution. The output  $y(n)$  is cross-correlated with the input  $x(n)$ . That means, the output  $y(n)$  is convolved with  $x(-n)$  which is shown as follows

$$y(n) \otimes x(-n) = h(n) \otimes x(n) \otimes x(-n) = h(n) \otimes [x(n) \otimes x(-n)] \quad (5)$$

From PN sequence's excellent periodic autocorrelation properties as shown in Figure 1

$$x(n) \otimes x(-n) \approx \delta(n) \quad (6)$$

Therefore, from Equation (5)

$$h'(n) = y(n) \otimes x(-n) \approx h(n) \otimes \delta(n) = h(n) \quad (7)$$

where  $h'(n)$  is the sounding impulse response and  $h(n)$  denote the practical impulse response. In order to reduce error between  $h'(n)$  and  $h(n)$ , the chip rate  $T_c$  keeps as small as possible. Because, from figure 1, keeping the chip rate  $T_c$  small, the periodic autocorrelation function of PN sequence is more similar to the Dirac-pulse like periodic autocorrelation function of white noise, and the measurement channel impulse response is more accurate.

In order to improve the measurement precision, the frequency domain compensation method is derived. Equation (8) shown as following is obtained from Equation (7) by Fourier transform.

$$H'(f) = H(f) \times H\_Comp \quad (8)$$

where  $H'(f)$  denotes the measurement transmission function,  $H(f)$  is the practical transmission function,  $H\_Comp$  is the Fourier transform of PN sequence's autocorrelation

function. From figure 1,  $H\_Comp$  keeps bigger value because of PN sequence binary autocorrelation function characteristics. So the compensation method is as following

$$H(f) = H'(f) / H\_Comp \quad (9)$$

### 3. Channel Measuring Results

The low-voltage PLC channel transmission characteristics are measured with length 150m and 250m respectively in a laboratory. Sounding parameters are as following: PN sequence's chip rate is 20MHz (PN sequence period is 6.35 $\mu$ s),  $n$  the number of the linear feedback shift registers is 7, and sampling rate of the digital oscilloscope is 100MS/s. In order to verify sounding method's correctness, the channel sounding in frequency domain is generally implemented by using the vector network analyzer (VNA) to compare the sounding results based on PN sequence.

Figure 3 is the non-synchronous measurement results. where Figure 3(a), (c) are PLC channel normalization impulse responses and the period is equal to the period of PN sequences, Figure 3(b), (d) are PLC channel amplitude frequency response characteristics and their comparison with VNA's sounding results. Figure 3(b), (d) show the measurement results by PN sequence as a black line. The measurement results by VNA are shown as the grey line. From Figure 3(b), (d), these sounding results are basically consistent with each other in the frequency range within 10MHz. However, these sounding results do not provide an exact matching above 10MHz. The reason is PN sequence's chip rate is 20MHz and the resolution of the measurement system is not better than  $1/2T_c$  which is equal to 10MHz.

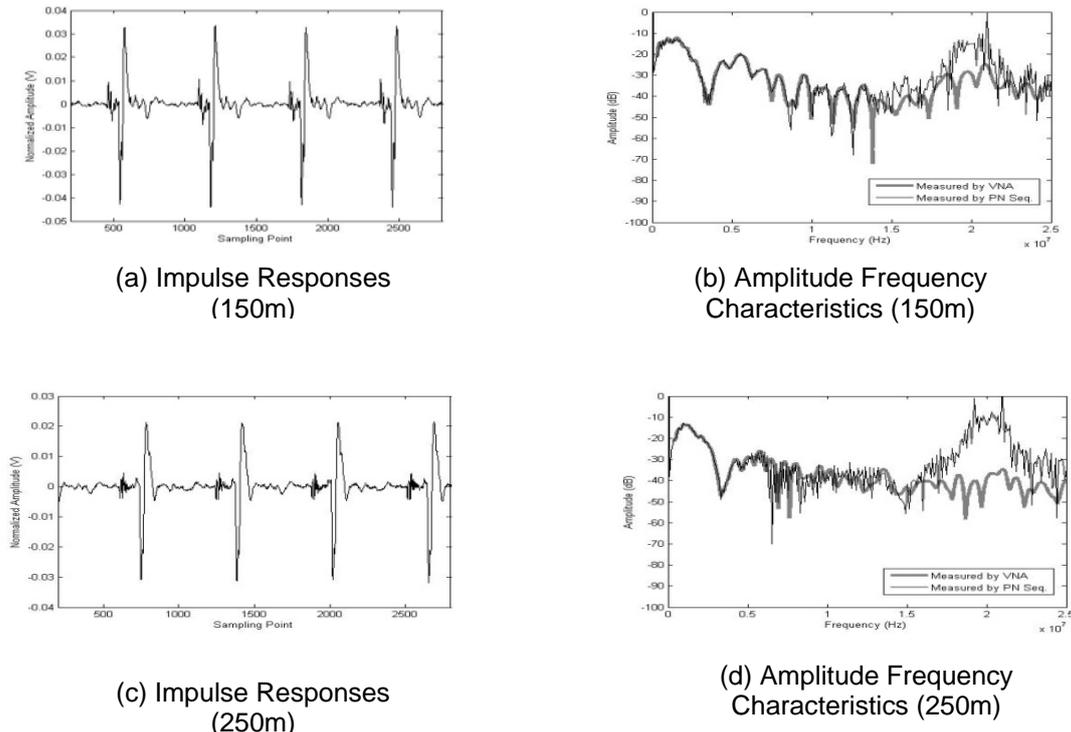


Figure 3. Measured Impulse Responses and Amplitude Frequency Characteristics of the Power Line Channel (Non-synchronous Measurement)

Figure 4 is the synchronous measurement results including PLC channel normalization impulse responses, amplitude and phase frequency response characteristics and their comparison results. The same conclusion is obtained that these sounding results basically consistent respectively in the frequency range within 10MHz. Meanwhile, comparing these sounding results, the absolute value maximum of channel impulse response with length 150m is

0.04274V, with length 250m is 0.0308V. The phenomenon describes the conclusions that the channel attenuation characteristics can increase with the length of power line cables.

#### 4. Modelling of Channel Measurements and Discussion

In order to get an accurate understanding of the complete characteristic of the PLC channel, measurement campaign was conducted in a company laboratory environment as shown in Figure 5. Sounding parameters are the same as mention above. In Figure 5, the transmitter was fixed at outlet F, and the receiver was located at outlet B, outlet E and outlet I. The impulse responses were measured 100 times per every measurement.

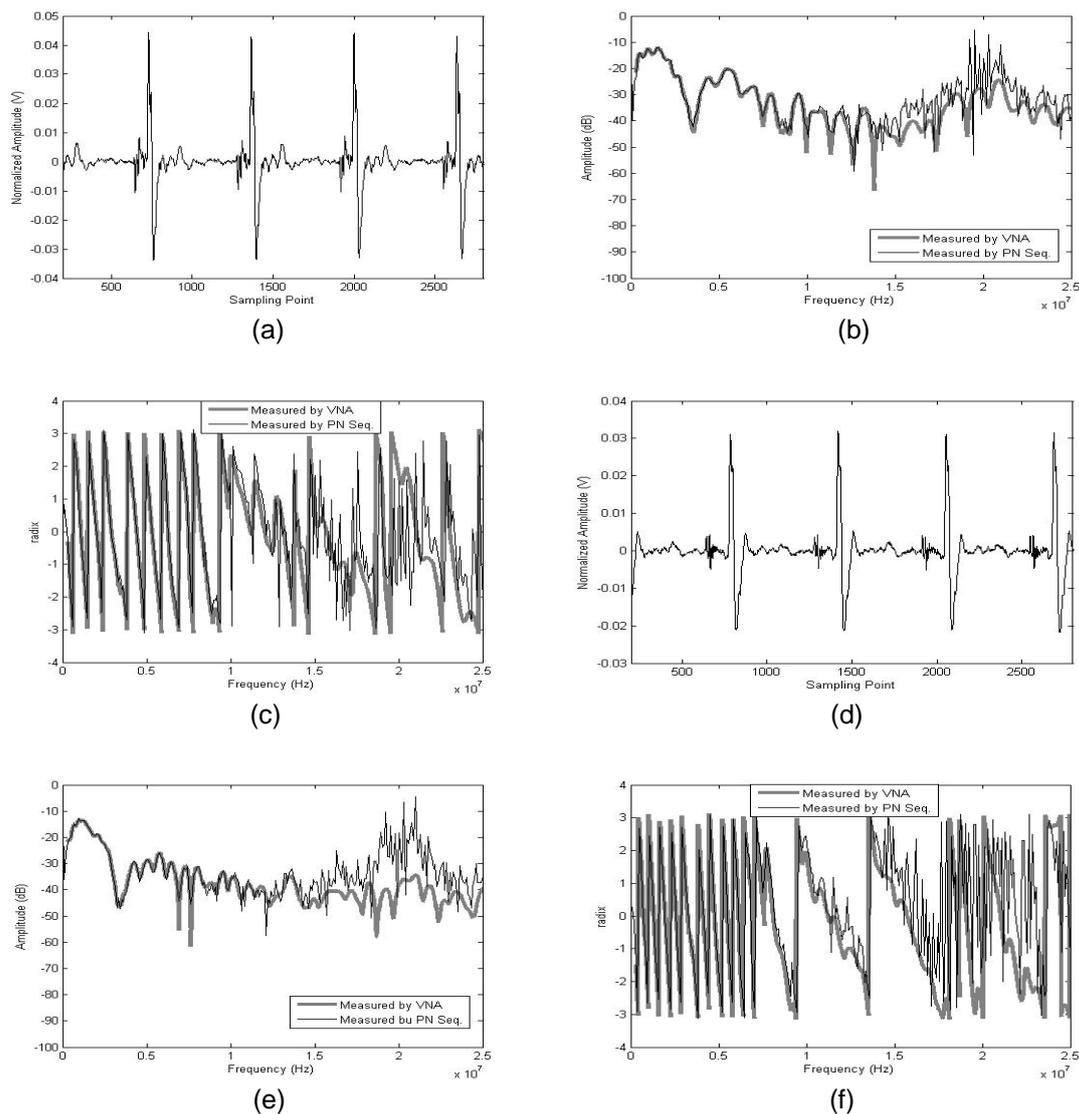


Figure 4. Measured Synchronous Measurement Results of the power line channel. (a) Impulse Responses (150m), (b) Amplitude Frequency Characteristics (150m), (c) Phase Frequency Characteristics (150m), (d) Impulse Responses (250m), (e) Amplitude Frequency Characteristics (250m), (f) Phase Frequency Characteristics (250m)

The resulting impulse response in the time and frequency domain respectively measured at outlet B is shown as figure 6 and figure 7. Figure 6 depicts the significant delay-spread for channel impulse response affected by multipath effects. The multipath nature of the

power line channel arises from the present of several branches and impedance mismatches that cause multiple reflections. Obviously, the more the multiple reflections are, the more delay spread increases. From the resulting impulse response, amplitude frequency response characteristics can be obtained using the Fourier transform as shown in Figure 7.

For modelling indoor PLC, the empirical multipath channel model for power line is proposed. Indoor cable length is relatively short and the attenuation can be neglected. Therefore, the paper proposes a channel model without low-pass attenuation based on measured data. Specifically, modelling of channel measurement as the impulse response is reduced to a sum of weighted Dirac-impulses. Figure 8 is shown impulse response measurement and modelling in the time and frequency respectively domain measured at outlet B. In figure 8 the result of a channel measurement is shown as a grey line and the modelling of the channel is represented by the black line.

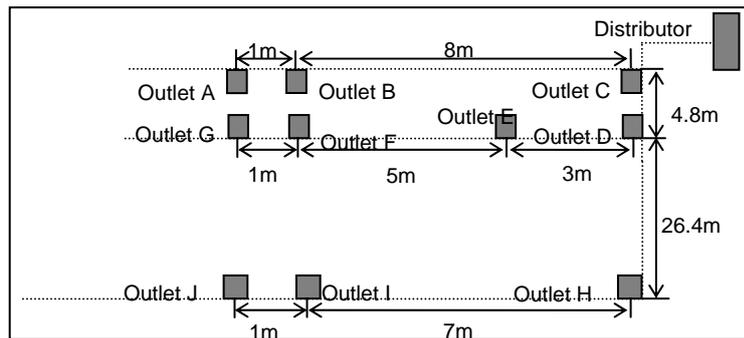


Figure 5. Floor Plan and Layout of Power Outlets

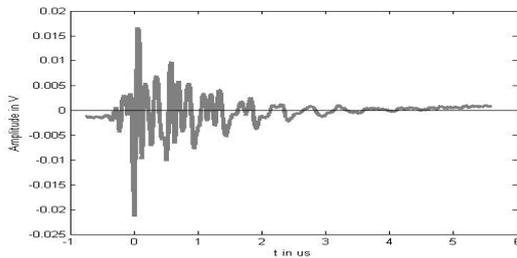


Figure 6. Impulse Response in Time Domain Measured at Outlet B

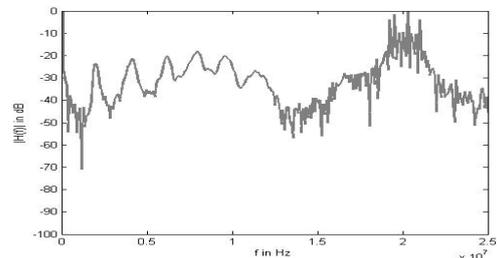
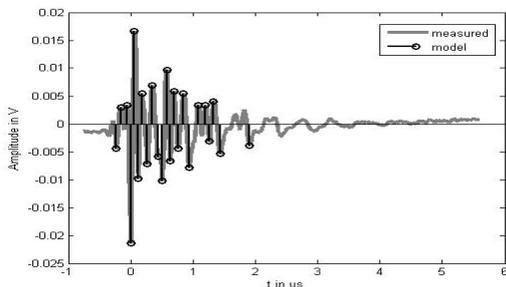
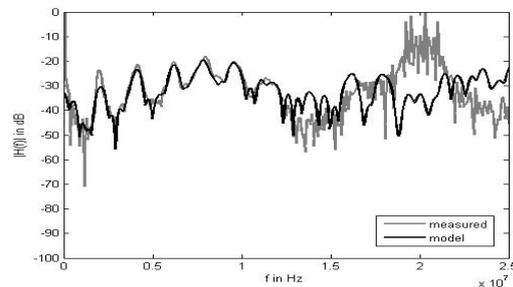


Figure 7. Impulse Response in Frequency Domain Measured at Outlet B



(a) Impulse Response (23 paths)



(b) Amplitude Characteristics

Figure 8. Measurement and Modeling Measured at Outlet B

From Figure 8(a), only those echoes have been extracted from impulse response whose absolute amplitude does not under-run the absolute maximum of impulse response, with more than 15dB. Therefore, the threshold value is important. Obviously, the smaller the

threshold values, the higher the number of considered paths are, and the longer is the modelled impulse response. As shown in Figure 8(b), the amplitude characteristics of the channel measurement are basically consistent with the amplitude characteristics of the channel model. Therefore, Figure 8(b) illustrates the efficiency of the modelling.

Table 1 has a summary to the data collected from the results of the measurement. Where  $\bar{N}$  denotes the average the number of the multi-paths,  $\bar{\tau}$  is the mean excess delay,  $\bar{\sigma}$  is the averages RMS delay spread, maximum and minimum amplitude give limits for the amplitudes of single impulses. From Table 1 all indices have a tendency to increase as the length of power line. The statistical results is reasonable because the attenuation and delay spread for PLC channel have not only more length of the cable itself but also more reflections due to the impedance mismatches at branch and end points in the network topology.

The distribution of the amplitude, which is obtained from measured impulse responses at outlet B and outlet E relatively, is presented on the histogram of Figure 9. As shown in Figure 9, the amplitudes are decaying exponentially.

Table 1. Measurement Results

Outlet	$\bar{N}$	$\bar{\tau}$ [us]	$\bar{\sigma}$ [us]	Maximum amplitude[V]	Minimum amplitude[V]
B	21.2	1.0845	0.3919	0.0213	0.0018
E	20.4	0.9986	0.3573	0.0318	0.0054
I	24.5	1.0104	0.4316	0.0173	0.009

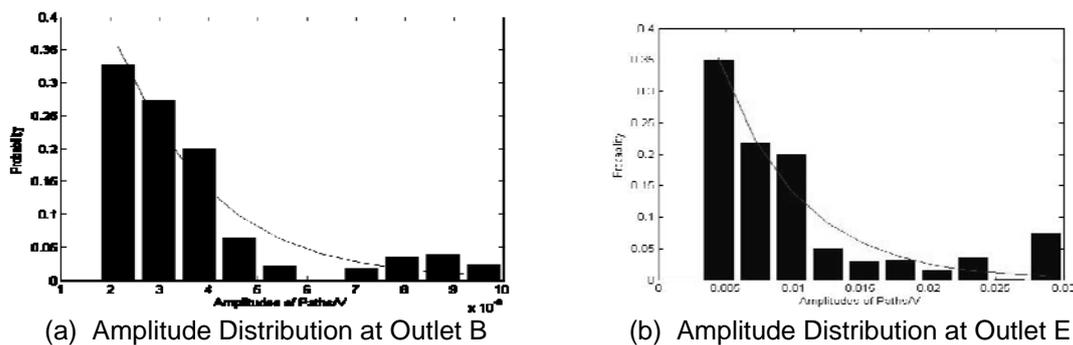


Figure 9. Histogram of the Amplitude Distribution

## 5. Conclusion

In this paper a method for measuring the transmission characteristics of the power line channel is presented. Using the PN correlation method, the impulse responses, reliable amplitude and phase frequency response characteristics of a power line channel can be measured. The measurement method has the advantages such as fast speed, easy measurement, etc. Meanwhile, from impulse response measurements, the channel properties of power line are characterized and the empirical multipath channel model of power line is proposed. Finally, the statistics of the proposed model normalized amplitudes and channel delay spread are analysed.

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