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Modeling of Transfer Characteristics for the Broadband Power Line Communication Channel

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Abstract—This paper presents a novel approach to model the transfer function of electrical power lines for broadband power line communication. In this approach, the power line is approx- imated as a transmission line and the two intrinsic parameters, the characteristic impedance and the propagation constants, are derived based on the lumped-element circuit model. Using these intrinsic parameters, the transfer characteristics for a N-branch power distribution network are derived based on the scattering matrix method. Detail derivation of this line model is given in thispaper. The model has been verified with practical measurements conducted on actual power networks. It is demonstrated that the model accurately determine the line characteristics under different network configuration and when different household appliances are connected.
Index Terms—Channel modeling, communication channel, power line communications.

INTRODUCTION

IN 1995, the power line communication (PLC) formally joined the family of broadband wired communication systems after NOR.WEB demonstrated the technical feasibility for the transmission of the high-frequency ( ) signal on the low-voltage (LV) power lines [1]. It is obvious that there are many advantages in using a power line network as a communication channel. Firstly, the power network is the most pervasive network comparing to any other networks in the world and its availability reaches every sockets in our house. Secondly, the installation of the PLC system is very cost effective, since it makes use of existing power lines and no
additional wires are required.

However, unlike the other wired communication mediums such as the unshielded twisted pair (UTP) and coaxial cables, LV power lines present an extremely harsh environment for the high-frequency communication signals. The three critical channel parameters namely, noise, impedance and attenuation,are found to be highly unpredictable and variable with time, frequency and location [2]. In order to overcome these difficul- ties, a lot of efforts have been undertaken to characterize and model the LV power line channel.

The objective of this paper is to develop a transfer character- istic model for the LV power line based on the transmission line theory. This model will help the PLC system designer to betterunderstand the channel behaviors and to engineer the channel

0performance under different network configurations and load conditions.

Section II reviews existing modeling approaches for PLC and compares their advantages and disadvantages. That is followed by the derivation of the power line parameters using the transmission line theory. These parameters are later usedto determine the transfer characteristics of the PLC channel. A sample network with multiple branches and connected with typical household appliances are constructed to verify the validity of this model through practical measurements.

LITERATURE REVIEW

In literature, several techniques have been introduced to model the transfer characteristics of power lines. Basically, there are two essential factors in these models: the modelparameters and the modeling algorithms. These two factors determine the reliability and accuracy of the model.
From the ways the model parameters are obtained, themodeling technique can be classified into two approaches:the top-down approach and the bottom-up approach. In thetop-down approach, the model parameters are retrieved frommeasurements [3]–[7]. This approach requires little computa- tion and is easy to implement. However, since the parameters depend on the measurement results, the model is prone tomeasurement errors. On the contrary, the bottom-up approachstarts from theoretical

derivation of model parameters [8]–[10]. Although this approach requires more computational efforts comparing to the top-down approach, it however describesclearly the relationship between the network behavior and themodel parameters. Morever, this modeling approach is more versatile and flexible since all the parameters are formulated, making it easy to predict the changes in the transfer function should there be any change in the system configuration. The model described in this paper adopts this bottom-up approach.Depending on the modeling algorithms used, the above ap- proaches can be achieved in the time domain or the frequencydomain. In time-domain modeling, the power line channel is re-garded as a multipath environment and an echo model is de-veloped to represent this physical characteristic [3]–[5], [8].This modeling is simple to implement in the top-down approach [3]–[5], but in the bottom-up approach, it is based on the ap- proximation that the backward reflections from impedance dis-continuities are negligible [8]. In addition, the echo model alsobecomes fairly complex when multiple branches are connectedat a common joint. In frequency-domain modeling, the networkis regarded as a composition of many cascade-distributed por-tions. Then the whole network behavior can be described based

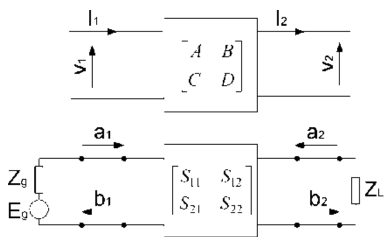


Fig. 1. Comparison of transmission matrix and scattering matrix of 2-port network.

on the transmission matrices or the scattering matrices of the cascaded portions [6], [7], [9], [10]. The main advantage of the frequency-domain modeling is its ability to consider all the sig- nals reflected from the discontinuities regardless of the com- plexity of the network.

Currently, there are a few frequency-domain models that are based on the complete bottom-up approach [9], [10]. The model parameters can be derived from the eigen analysis of multicon- ductor network matrices [9] or from the lumped-circuit trans- mission line model [10]. The former method involves many pa-rameters that are difficult to determine with sufficient accuracy.The typical modeling algorithms used are either transmission matrix [10] or the scattering matrix [9] as shown in Fig. 1. In this paper, the scattering matrix method is chosen ahead of the transmission matrix method due to the following reasons.

The transmission matrix gives the relationship of the voltage( ) and current ( ) at the two terminals while the scattering matrix gives the relationship of the incident ( ) and reflected( ) waves. The transfer function derived from the transmission matrix is basically , which is the transfer factor of the standing waves (including both incident and reflected waves). However, PLC is only interested in the transfer function in the forward direction, which is the ratio of the incident power into the receiver over the power injected by the transmitter. This can readily be expressed by b_2/a_1 or S_{21} in the scattering matrix.

With the above arguments, a novel bottom-up approach based on the frequency-domain modeling and using scattering matrix is proposed in this paper. The two model parameters, the charac- teristic impedance and the propagation constant, are first derived using a lumped-element circuit model. Then the frequency-do-main modeling based on the scattering matrices is applied to account for the many branches in the power line.

The focus of this paper is on the in-house power lines found in a typical household in Singapore. The power lines are usu- ally laid inside metal conduits and the PLC frequency range of interest is taken as between 1-30 MHz (following ETSI require-ments for first-generation PLC [11]).

TRANSMISSION LINE ANALYSIS OF POWER LINE

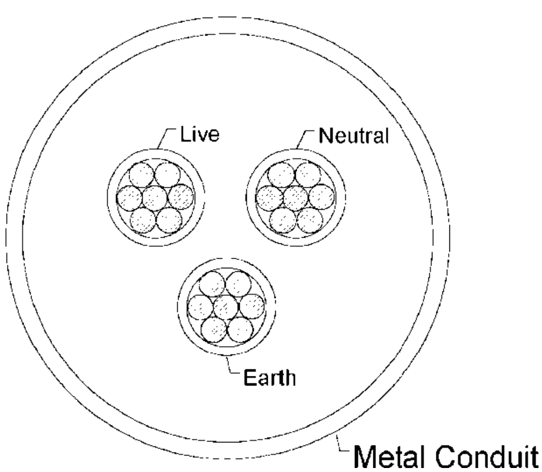


Fig. 2. Cross-sectional view of the house service power line.

Fig. 2). The cables are made up of stranded copper conductors with PVC insulation. The three cables (live, neutral, and earth) are usually laid inside metal conduits that are embedded inside the concrete wall.

Typically, the live and neutral cables are used as the PLC transmission channel, which can be approximated as a close form of the "two-wire transmission line". According to [12], the two-wire transmission line must be a pair of parallel conducting wires separated by a uniform distance. In the actual installation, the power cables are simply pulled through the conduit and the separation between them is not uniform at all. However, the con- duit normally has small cross-sectional area and this limits the variation of the separation between the cables. Hence, the as- sumption of uniform separation is reasonable in this case.

Based on the above consideration, the paired power cables are regarded as a distributed parameter network, where voltages and currents can vary in magnitude and phase over its length. Hence,it can be described by circuit parameters that are distributed over its length.

In Fig. 3, the quantities $v(z,t)$ and denote theinstantaneous voltages at location and $v(z+\Delta z, t)$ respectively. Similarly, $i(z,t)$ and denote the instantaneous cur-rents at and , respectively. defines the resistance per unit length for both conductors (in Ω/m), defines the in- ductance per unit length for both conductors (in H/m), is theconductance per unit length (in S/m), and is the capacitanceper unit length (F/m).

Based on the lumped-element circuit shown in Fig. 3(b), the two intrinsic line parameters for the transmission line, i.e., the propagation constant and the characteristic impedance Z_0, can be written as [12]

The electromagnetic theory states that to achieve efficient point-to-point transmission of power and information, the source energy must be guided. When power lines are usedto transmit high frequency communication signals, they can be regarded as transmission lines, which guide the transverseelectromagnetic (TEM) waves along them.

The cable under study in this paper is the typical single-phasehouse wirings commonly found in Singapore (as shown in where is the angular frequency. The real part and the imag-inary part β of the propagation constant are the attenuation con-stant (in Np/m) and phase constant (in rad/m) respectively. Note that both and Z_0 are characteristic properties of a transmission

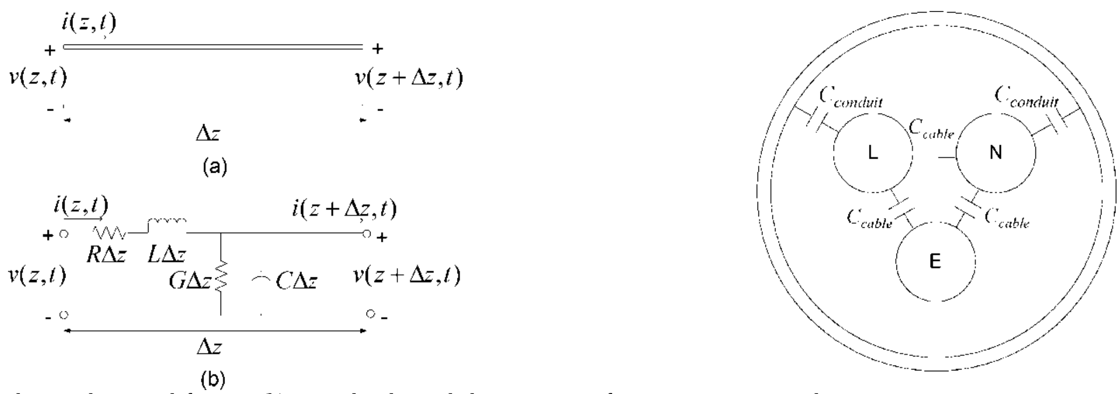


Fig. 3. (a) Voltage and current definitions (b) Equivalent lumped-element circuit of two-wire transmission line.

line even if the line is infinitely long. In other words, they de- pend on , , , , and , but not the length of the line.

With the power line being modeled as a transmission line, itsand Z_0 will dominate the wave behavior along the line. In the model proposed in this paper, they serve as the parameters tomodel the transfer function of the channel. In the next section, these two parameters are derived for the typical house power cables as shown in Fig. 2.

I. Determination of Model Parameters

In order to determine the two model parameters γ and Z_0, the four primary line parameters of , , , and have to be determined first.

A. Determination of Primary Line Parameters

1) Resistance: When an ac current flows in a conductor, the self-inductance within the conductor causes more current to flow near to the outer surface of the wire instead of toward the center. This phenomenon is called the skin effect [12]. Thiseffect causes an increase in the resistance of the cable and it worsens as the current frequency increases. Although the cur- rent flow is still distributed throughout the cross section of the cable, when calculating the resistance, it is normal to assume that all the current flows within the "skin depth" of the cable. The skin depth ( ) is a function of frequency (f) and can be cal-culated using the equation

$$\delta = \sqrt{\frac{1}{\pi f \mu_c \sigma_c}} \quad (3)$$

where and are the conductivity and permeability of the conductor, respectively. So, for a two-wire transmission line with solid core conductor, the resistance can be obtained as

$$R_{\text{solid}} = \frac{1}{\pi a \delta \sigma_c} \; (\Omega/\mathrm{m}) \quad (4)$$

Fig. 4. Equivalent capacitance diagram in power line (L: live, N: neutral, E: earth).

of a solid core cable, which has the same overall radius. This ratio is given by [13]

$$X_R = \left[\cos^{-1}\left(\frac{r_{\text{wire}} - \delta}{r_{\text{wire}}}\right) \times r_{\text{wire}}^2 - (r_{\text{wire}} - \delta)\sqrt{r_{\text{wire}}^2 - (r_{\text{wire}} - \delta)^2}\right] / (2 \times r_{\text{wire}} \times \delta) \quad (5)$$

where r_{wire} is the radius of a single wire in the stranded con- ductor and δ is the skin depth given by (3). With this correction factor, the final resistance for the stranded cable is

$$R = X_R \, R_{\text{solid}} \; (\Omega/\text{m}) \quad (6)$$

2) Inductance: The inductance of the two-wire transmission line includes the self-inductance for each conductor and the mu- tual inductance between them. From [12], the self-inductance for one conductor is given by

$$L_s = \frac{\mu_0}{8\pi} \; (\text{H/m}) \quad (7)$$

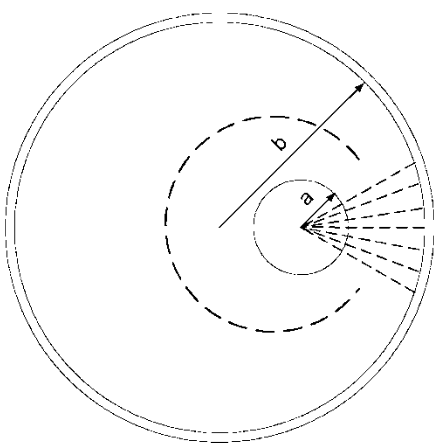
and the mutual inductance between a pair of parallel conductorsis

$$L_m = \frac{\mu_0}{\pi} \ln\left(\frac{D - a}{a}\right) \; (\text{H/m}) \quad (8)$$

in which D is the distance between conductors. So, the total inductance can be obtained as

$$L = 2L_s + L_m = \frac{\mu_0}{\pi}\left[\frac{1}{4} + \ln\left(\frac{D - a}{a}\right)\right] \; (\text{H/m}) \quad (9)$$

3) Capacitance: From Fig. 2, the cables are not exposed to free space but are laid inside a metal conduit. Moreover, because of the presence of the earth cable in the conduit, the capacitive coupling effects from both the conduit and the earth cable cannot be ignored. These coupling effects are considered as equivalent capacitances as shown in Fig. 4. C_{cable} is the cable-to-cable capacitance per unit length, which can be represented by the ca- pacitance given in (10). C_{conduit} is the cable-to-conduit capac-itance per unit length. Note that there is no capacitance between the earth cable and the outer conduit because both of them are usually connected to ground and hence there is no electric po- tential between them.



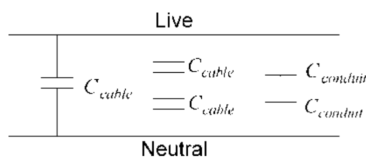


Fig. 6. Total capacitance between paired cables.

of the two C_{conduit} represents the coupling introduced by the metal conduit. The total capacitance can then be written as,

C + C −

$C = C$ $+$ cable

cable C can be regarded as the capacitance of the two-wiretransmission line, which is given by [12] as

$$C_{cable} = \frac{\pi\varepsilon}{\ln\left[\left(\frac{D}{2a}\right) + \sqrt{\left(\frac{D}{2a}\right)^2 - 1}\right]} \text{ (F/m)} \quad (10)$$

where is the permittivity of the dielectric material in betweenthe conductors.

The determination for $C_{conduit}$ is more complicated since the cable and the conduit are in the eccentric coaxial position. This kind of capacitance can be solved by conformal mapping method or perturbation method. In this paper, a simpler analytic method based on segmentation is used.

As shown in Fig. 5, taking the center of the inner conductor as the origin, the radial axes are used to segment the eccen-tric coaxial conductors into N sectors. When $N \rightarrow \infty$, each sector can be approximated as one segment in the coaxial cylin-drical conductors. The capacitance for the coaxial cylindrical conductor is given in [12]

$$C_{coaxial} = \frac{2\pi\varepsilon}{\ln\left(\frac{b}{a}\right)} \text{ (F/m)} \quad (11)$$

where b is the inner radius of the outer conductor. Based on the segmentation method, the capacitance between the cable con-ductor and metal conduit as shown in Fig. 4 can be taken as theaverage capacitance of all segments

$$C_{conduit} = \lim_{N\rightarrow\infty} \sum_{k=1}^{N} \frac{1}{N} \frac{2\pi\varepsilon_k}{\ln\left(\frac{b_k}{a}\right)} \text{ (F/m)} \quad (12)$$

where ε_k and b_k are the permittivity of the dielectric material and the inner radius of the metal conduit for sector k.

Considering Fig. 4, the high-frequency communication sig-nals are not only coupled by C_{cable} between paired cables, butthey are also coupled from the live cable to the earth cable first and then couple from the earth cable to the neutral cable. Theycan also be coupled from the live cable to metal conduit and then from conduit to the neutral cable. Hence, the total capacitance can be summarized as in Fig. 6.

The series connection of the two C_{cable} represents the cou- pling introduced by the earth cable while the series connection

4) Conductance: From [12], if the medium has the same space dependence or if the medium is homogeneous, the fol- lowing equation holds:

$$\frac{C}{G} = \frac{\varepsilon}{\sigma} \Rightarrow G = \frac{\sigma \cdot C}{\varepsilon} \quad (14)$$

where σ is the conductivity of the dielectric material and G is the cable conductance.

For the house power cables as shown in Fig. 2, the dielectricmaterial, either between the cable conductors or between cable conductor and conduit, is inhomogeneous in both space (due tothe round shape of the cable conductor) and contents (mixture of insulation and air). But since the cables are of close proximity to each other, the thickness of the insulation is comparable withthat of the air space between the conductors. In this paper, the dielectric is assumed to be just a mixed content material and theeffects of the inhomogeneous in space are neglected to keep themodel tractable.

B. Verification of Model Parameters

After deriving all the primary line parameters, (1) and (2) can be applied to determine γ and Z_0. They can be verified by measuring the input impedance of a line section under open- circuited and short-circuited conditions. From the transmissionline theory, the input impedance looking into a line with length l and termination load Z_L is

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh(\gamma \cdot l)}{Z_0 + Z_L \tanh(\gamma \cdot l)} (\Omega). \quad (15)$$

If the load terminal is short-circuited, i.e., $Z_L = 0$, (15) be- comes

$$Z_{is} = Z_0 \tanh(\gamma \cdot l)(\Omega). \quad (16)$$

Similarly, if the load terminal is open-circuited, i.e., $Z_L \rightarrow \infty$, (15) becomes

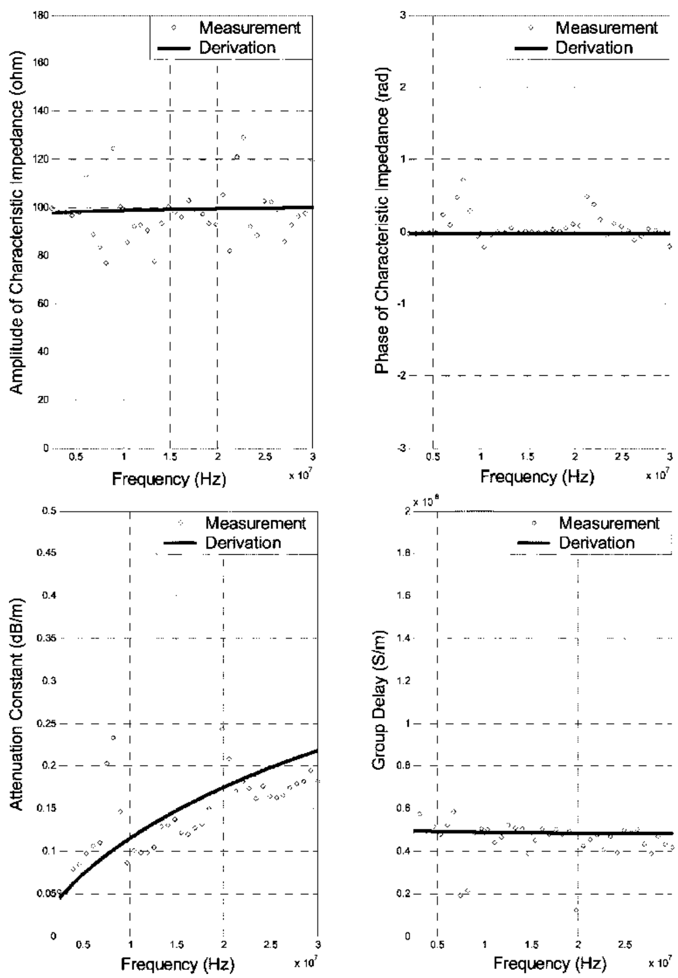
$$Z_{io} = Z_0 \coth(\gamma \cdot l)(\Omega). \quad (17)$$

From (16) and (17)

$$Z_0 = \sqrt{Z_{is} Z_{ic}} \quad (18)$$

$$\gamma = \frac{1}{l}\tanh^{-1}\sqrt{\frac{Z_{is}}{Z_{ic}}} \quad (19)$$

It should be noted that when the cable length is equal to mul-tiples of the quarter wavelength of the operating signal, then



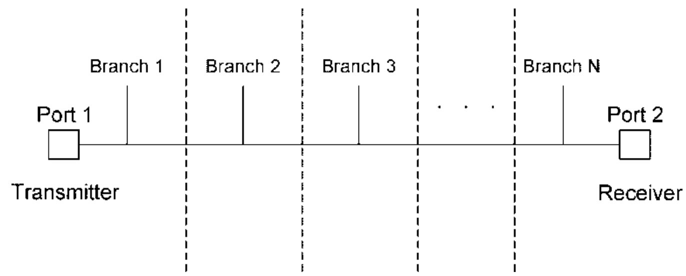


Fig. 7. Comparison of measured and derived. (a) Amplitude and phase of characteristic impedance (b) Attenuation constant and group delay.

Z_{is} and Z_{ic} would be either zero or infinity. This quarter wave- length effect can be easily viewed on the Smith's chart. At a certain frequency, the input impedance of a short termination (or open termination) will become open circuit (or short circuit) when the cable length is equal to odd multiples of the signal's quarter wavelength and will become short circuit (or open cir-cuit) when the cable length is equal to even multiples of quarterwavelength. In such cases, measurements will be erroneous andthe results should not be considered. Because of this, in the ver- ification measurements, several lengths of power lines are usedand those results affected by the above quarter wavelength phe-nomenon are ignored.

Fig. 7 compares the measured and the derived characteristic impedance (Z_0), attenuation constant ( ) and group delay ( ), which represents the time needed for a signal to travel 1 m τ

$$\tau = \frac{d\beta}{d\omega} \text{ (S/m)} \quad (20)$$

The cable used in the measurement has a 4 mm^2 cross-sec- tional area, and the inner radius of the metal conduit is 15 mm. Measurements are done over the frequencies of .

From the comparison, it can be seen that the derived 1-30 MHz pa-rameters match closely to the measured values most of the time.This confirms the validity of this modeling approach.

II. TRANSFER FUNCTION MODELING

With and Z_0, the transfer function of the PLC channel can be determined. The different mechanisms by which the PLC signal is attenuated need to be understood. There are three main types of attenuation for a wave propagating in the forward direction. The first one is the line attenuation, which is caused by the heat loss and radiations along the power line. This line attenuation is always present and it depends on the length of the wave path and the frequency of the wave. The second type of attenuation is caused by reflections arising from the points of impedance discontinuities on the propagation channel. The reflected wave from the unmatched points will interfere with the original incident wave. This kind of interferences may be constructive or destructive, giving rise to attenuation if it is destruc-tive. The last type of attenuation is caused by the delayed version of the forward propagating wave falling out of phase with the main incident forward wave, giving rise to destructive interference and hence overall signal attenuation.

As a result, frequency-domain modeling approach is sug-gested because it is very hard to use the time-domain modeling approach to account for all these reflected and delayed paths in the power network. Since most in-house power line network installations in Singapore are radial, the PLC channel can be regarded as a -branch network as shown in Fig. 8 below. Obtaining the scattering matrix of such a network is quite complex and hence in this paper, the channel is divided into a group of cascaded single-branch networks. The scattering matrix for each single-branch network is derived in the following section and the scattering matrix of the whole channel can then be determined by using the chain-scattering matrix method.

To analyze the -parameters of a single-branch network, the following diagram shown in Fig. 9 is used. In this derivation, the power line on the direct signal path (excluding the branches) is defined as the path line.

Let l_1 be the cable length from left end of the path line to the tap point, l_2 the cable length of the cable branched off from the tap point and l_3 the cable length from the tap point to the right end of the path line. Using transmission line theory, Z_{in1}, Z_{in2}, Z_{in}, Γ_1, and Γ_2 can be determined

where T_k is the -matrix for the -th cascaded portion in the network. Finally, the -matrix for the whole network can be obtained by using the following conversion equation:

$$S = \begin{bmatrix} S_{11} & \\ S_{21} & \end{bmatrix} = \begin{bmatrix} \frac{T_{21}}{T_{11}} & T_{22} - \frac{T_{21}T_{12}}{T_{11}} \\ \frac{1}{T_{11}} & \frac{T_{12}}{T_{11}} \end{bmatrix} \quad (34)$$

The S_{21} term in (34) gives the network transfer function.

To verify the above derivations, the transfer function for a network with three branches as shown in Fig. 10 is measured. Loads 1, 2, and 3 in the network under test are light dimmer, TV,

and then substitute (29), (30), and (31) into (28), can be obtained. Similar method can be used to determine and S_{22} by simply swapping the source and load locations.

After analyzing the single-branch network, the remaining task is the determination of the scattering matrix for a cascade of several single-branch networks. Using the microwave theory, there are generally two methods that can be used. The first method is to use the chain scattering matrix (or -matrix), and the second is to use signal flow graph. For the sake of easier computation, the first method is used in this paper.

and electric fan, which are typical household appliances. All the loads are in operating condition. The measured impedances of these electrical appliances over are given in the Appendix .

In Fig. 11, the amplitude and the phase angle of the derived transfer functions for this 3-branch network are compared with those obtained from measurements. It can be seen that the de- rived and measured transfer functions match each other closely, demonstrating that the model can accurately predict the channel transfer function of the PLC medium including the positions of

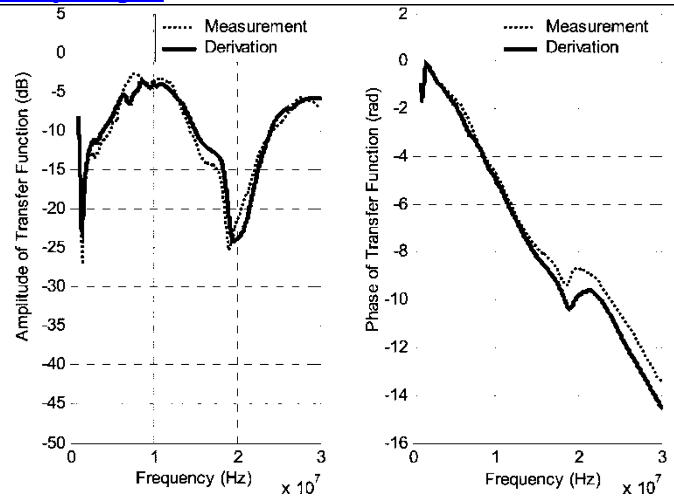
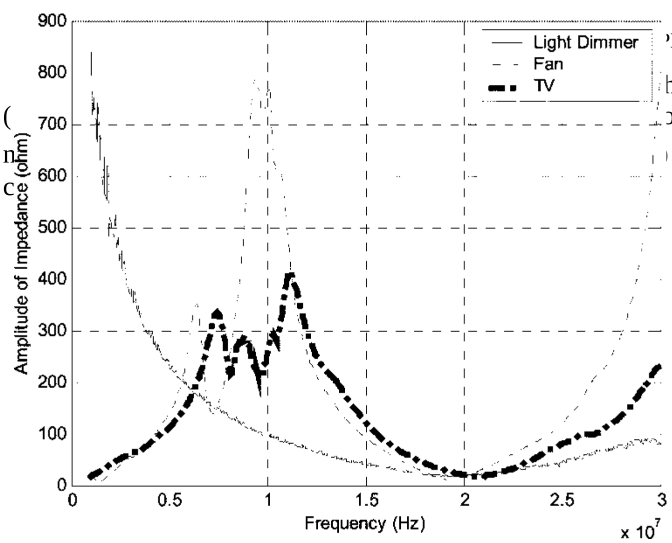


Fig. 12. Comparison of derived transfer function with measurement after thechange of the load condition.

in different configurations, as long as the construction and di- mension of the power cables are known.

VI. Conclusion

In this paper, the LV single-phase power line is modeled as a transmission line to compute the two intrinsic line parameters namely, the characteristic impedance and the propagation con- stant. The model takes into consideration of the type of cable used and the cable mounting method. Making use of these in- trinsic parameters as the model parameters, the LV power net- work is then regarded as an -branch network, which is sub- divided into several cascades of smaller networks. The channel transfer function is later determined by combining the scattering matrices of the cascaded subnetworks. Both the model parame-ters and the transfer characteristics have been verified success-fully through practical measurements on actual power line.



ENDIX

(hod proposed in [16]. The impedance of the power network
n ot connected to the network. Then, the appliance is connected
c is again measured. The impedance of the appliance (app) can be

$$\frac{1}{Z_{net2}} - \frac{1}{Z_{net1}} + \frac{1}{Z_{app}}$$

Rearranging (39),

we get

$$Z \;-\; \frac{Z}{Z} \quad \frac{Z}{-\,Z} \quad app \quad \frac{net1 \quad net2}{net1 \quad net2}$$

1 ~ 30 MHz

Fig. 13 shows the measured impedances of the light dimmer,electric fan and TV in the frequency range of . These impedances were used in the derivation of transfer func-tion of the network in Fig. 10 that was used for verification pur-poses.

attenuation notches in the frequency domain. The strong attenu-ation notch at about 20 MHz is mainly caused by the impedances of the branched loads. It can be observed in Fig. 13 that all thethree loads have very small impedances at frequency around 20MHz. As a result, the majority of the signals in this frequency range will be shorted out when they travel along the channel.

To demonstrate the flexibility and versatility of this model, Load 1 (light dimmer) is unplugged from the network. The newly derived and measured transfer functions are then com- pared as shown in Fig. 12. The strength of the attenuation notchnear 20 MHz has reduced to about 25 dB. Once again, boththe measurement and derivation results match closely to each other, verifying the capability of this model in predicting the behavior of the power line channel.

Knowing the characteristics of the power line channel will be of great help in analyzing the performance of different communication schemes as well as identifying potential difficulties.This modeling approach can be used to model power networks

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