J Electr Eng Technol.2018; 13(1): 521-531
http://doi.org/10.5370/JEET.2018.13.1.521

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Characterization and Field Measurements of NB-PLC for LV Network

Bilal Masood†, Manzoor Ellahi*, Waheed Aftab Khan*, Waqar Akram*, Muhamad Usman and Muhammad Talha Gul***

Abstract – This paper presents a procedure for field measurements which provides a generalized Narrowband Power Line Communications (NB-PLC) channel model for low voltage (LV) access network in order to deploy advanced metering infrastructure (AMI) within Lahore, Pakistan. The measurements of allocated sites were performed in the residential (urban and rural), industrial and commercial electricity consumers for the NB-PLC channel modeling of overhead transmission lines (TLs). On the basis of extensive field measurement results, the average attenuation profile and transfer functions are presented. The results obtained from field measurements are validated by comparing them with a proposed Simulink model. A close agreement in the measured and simulated transfer function (TF) results is observed. The proposed Simulink model is an effort to model the NB-PLC channels in an effective way, especially in South Asian countries.

Keywords: AMI, Distributed parameter line, NB-PLC

1. Introduction

In the last few years, a massive increase in distributed generation (DG) and renewable energy systems (RES) has been observed. Main reason of this increase is the increasing demand of electricity with the passage of time. Further, the 20/20/20 (20% increase of energy efficiency, 20% increase of RES and 20% decrease in CO_x and NO_x emission) goal can be achieved with the incorporation of distributed energy systems [1]. The continuous use of RES and DG adds the complexity in the electric power network that need to be solved. A complete rethinking is required to overcome such kind of problems that can be resolved by using information and communication technologies (ICT) for AMI. A simple model of AMI is shown in Fig. 1. A large number of communication technologies which includes wireless and wired communication are available for AMI, both have their own advantages and disadvantages. Main wireless communication technologies are GPRS, GSM, WiMAX, UMTS, Wifi, WLAN, HiperLAN and ZigBee etc [2]. On the other hand wired communication based power line communication (PLC) has its promising feature like already existing infrastructure in form of electric power transmission and distribution network. The implementation of PLC technology decreases considerable amount of operation and maintenance (O & M) cost. PLC is categorized into three major classes in which Ultra Narrowband (UNB) operated on 0.3-3 kHz, Narrowband (NB) used in distribution lines with frequency range 3-500 kHz and Broadband (BB), 1.8-250 MHz are included [1]. This paper is utilizing the CENELEC-A band of NB-PLC that ranges from 9 to 95 kHz. However all presented analyses are following the frequency range from 40-90 kHz of CENELAC-A band.

The paper presents the field measurements and proposed simulation model for the analysis of a project assigned by Lahore Electric Supply Corporation (LESCO) to check the possibility of NB-PLC within AMI in Lahore. Novelty of this research work lies in the comprehensive analysis of NB-PLC channel for attenuation characteristics from both field measurements and proposed simulation model so that it can be evaluated whether NB-PLC is a suitable solution for AMI in Lahore or not. Such kinds of field trials have not been conducted previously, specifically in Pakistan. After field trials an average channel model of Lahore has been plotted whose results are validated with the results of proposed simulation model. The paper is divided into six sections. Section 2 compares the various NB-PLC channel models available in the literature. Section 3 presents the NB-PLC system that is under evaluation for field trials to characterize the power line channel. Section 4 describes the proposed simulation model. Finally section 5 is about results discussion followed by conclusions.

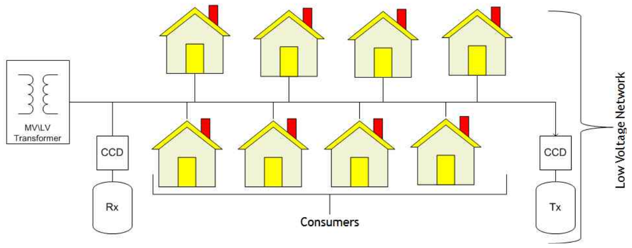


Fig. 1. NB-PLC system model

---

† Corresponding Author: Dept. of Electrical Engineering, the Superior College, University Campus, Lahore, Pakistan. (bilal.masood@superior.edu.pk)
* Dept. of Electrical Engineering, the Superior College, University Campus, Lahore, Pakistan.
** Dept. of Electrical Engineering, the University of Lahore, Lahore, Pakistan.

Received: June 16, 2016; Accepted: September 11, 2017

2. Comparison of Various NB-PLC Studies

The channel modeling of NB-PLC has vital significance in the perspective of NB-PLC deployment. It is particularly important to evaluate the characteristics of powerline channel that will be used for data and information communication through it. Since NB-PLC channel is hostile with reference to its characteristics, therefore special attention is paid while characterizing and modeling the NB-PLC channel. Major limitations of NB-PLC are noise factor, channel multipath and continuously varying access or load impedances that lead to degrade the quality of signal injected in the powerline. In order to overcome these challenges, several authors have proposed their solutions. Due to the fact that PLC is used to operate on various frequency bands, a single solution to model the PLC channel cannot fix the problem. So channel modeling of PLC is categorized into four main categories such as deterministic PLC channel models [3-7] statistical PLC channel models [8-11], measured PLC channel models [12-18] and parametric PLC channel models [1, 14, 19-21]. However, a comprehensive comparative analysis of various NB-PLC channel modeling techniques is presented by Bilal Masood et al. in [1]. The key features of proposed work of above mentioned channel modeling techniques along with main contributors are tabulated in Table 1.

A significant work towards PLC channel models are presented by Stefano Galli, Andrea M. Tonello, Zimmermann, Justinian Anatory and Antonio Cataliotti etc. Most of the research work available on the deterministic PLC channel models are on Indoor channel models, however in the past years implementation of deterministic PLC channel models has also been observed on outdoor LV and Medium Voltage (MV) power grid for the purpose of AMI [21]. The most followed methodology of deterministic PLC channel models is presented in [4-5], according to which each part of power network can be split approximately by following ABCD matrix based transmission line theory. The transfer function of PLC channel model can be determined by,

$$H = 20\log_{10}\frac{Z_L}{AZ_L + B + CZ_LZ_S + DZ_S} \tag{1}$$

where Z_S and Z_L are source and load impedances.

The resulting transfer function follows the symmetry property, means it is not dependent on the direction of signal injection either from sending end or receiving end. Therefore changing the position of transmitter installed whether at sending or at receiving end will not affect the resulted transfer functions [4-5]. However, in order to achieve the symmetry property, following conditions must be fulfilled,

- $|M|=1$ (resulting matrix's determinant must be equal to 1)
- Individually for all two port networks
  For any frequency, A=D
  For any frequency, B≠C
  $|Mi|=1$
- The internal resistance of transmitter and resistance of load will be equal.

Authors in [12-18], presented their research work for measurement based channel modeling techniques. Experimental evaluation and extensive field measurements for the characterization and modeling of PLC channels is performed. Field measurements of PLC are carried out by the incorporation of PLC based transceivers. In [12], state of the art to address the issues for the characterization of outdoor MV NB-PLC grid communication is proposed. Focus of proposed work was on the procedural and measurement based issues while implementing the NB-PLC for SG. Field measurements are carried out for the frequency range of 50-150 kHz and a sophisticated methodology to model and characterize the power system components is presented. The characterization of parameters like input impedance Z_{in} and characteristic impedance Z_C for MV network of length L is done by using transmission line theory approach given as,

$$Z_{in} = Z_C\frac{Z_L + Z_C\tanh(\gamma\times \text{l})}{Z_C + Z_L\tanh(\gamma\times \text{l})} \tag{2}$$

In case of load is short circuited then Z_L=0 and short circuit impedance Z_{sh} will become

$$Z_{sh} = Z_C\tanh(\gamma\times \text{L}) \tag{3}$$

Similarly when load is open circuited i.e., $Z_L=\infty$ then

$$Y_{open} = \frac{1}{Z_{open}} = \frac{1}{Z_C\coth(\gamma\times \text{L})} \tag{4}$$

From above two equations characteristic impedance Z_C is calculated as,

$$Z_C = \sqrt{\frac{Z_{sh}}{Y_{open}}} \tag{5}$$

Furthermore, another effective approach to model the characteristics of PLC channel is proposed by Zimmermann and Dostert that includes the multipath channel modeling approach based on statistical modeling. Authors proposed a multipath propagation model, which is expressed in a simplified form as [8],

$$H(f) = \sum_{i=1}^{N} g_i A(f,d_i)e^{-j2\pi f\tau_i} \tag{6}$$

where N represents the number of paths under considerations, g_i, $A(f, d_i)$ and $e^{-j2\pi f\tau_i}$ are attenuation due to reflections, attenuation on the line and delays due to distance respectively.

The subsequent section of this paper will describe the NB-PLC system that is under evaluation in the perspective of AMI.

3. NB-PLC System under Evaluation

This paper focuses on the project assigned by LESCO for possible low voltage NB-PLC for AMI in Lahore, Pakistan. Purpose of this project is to evaluate the performance of various sites of Lahore in order to characterize the power line channel for the CENELEC-A band [1]. Lahore consist of various types of electricity consumers that include residential, commercial and industrial type of loads. Several sites that can cater the characteristics of all types of possible channels have been allocated and provided by LESCO so that a comprehensive channel modeling can be performed are shown in Fig. 2. Selected sites and their salient attributes are tabulated in Table 2.

3.1 Field measurements for channel characterization

Field measurements are performed on allocated sites with

Fig. 2. Selected sites for field measurements

Table 1. Comparison of existing NB-PLC studies

Type of PLC model	Main contributors	Key features of proposed work	References
Deterministic PLC Channel Models	Stefano Galli et al.	• Multiconductor transmission line theory approach for coupled circuits • Analyzed the behavior of PLC for differential and pair mode circuits • Proposed a cascaded two port network model technique for efficient PLC	[3] - [5]
	Justinian Anatory et al.	• Modeled the transfer function of PLC channel • Derived the single phase PLC channel with interconnection by incorporating the various loads at different branches • Proposed model is validated with Transients Program–Electromagnetic Transients Program (ATP–EMTP)	[6], [7]
Statistical PLC Channel Models	Zimmermann et al.	• Multipath model • Caters the attenuation caused due to reflections and powerline • Incorporated delays due to length of line	[8]
	Andrea M. Tonello et al.	• Proposed a bottom-up PLC channel simulator • Derived in-home PLC channel model for Europe • Sophisticated computation method for channel transfer function • ABCD matrix based method is also proposed	[9] - [11]
Measured PLC Channel Models	Antonio Cataliotti, et al.	• Catered the issues involved in NB-PLC channel measurements • Proposed the suitable procedural techniques for modeling and characterization of power system components within the frequency of interest	[12] - [18]
Parametric PLC Channel Models	Canete et al.	• Impedance modeling for low voltage indoor PLC network • Proposed a simulator	[14], [19]
	Klaus Dostert et al.	• Modeled the access impedances by using series and parallel combination of resistance, inductors and capacitors • Prototype/test bed developed	[20]
	Bilal Masood et al.	• Frequency selectivity is added in resistance, conductance and impedances • Compared the transfer functions obtained from constant impedances with frequency selective impedances	[1], [21]

Table 2. Attributes of selected sites

Sr. No.	Site Name	Load Type	Attributes
1	Gaddafi Stadium	Commercial	Sports stadiums & complexes
2	Hafeez Center	Commercial	Computers & electric appliances based big mall
3	Kot Lakhpat	Industrial	Food, beverage and textile industries
4	Lahore Cantt	Residential	Urban population with aged PLC channel
5	Ghaziabad	Residential & Commercial	Congested rural population and bazaars with narrow streets
6	Township	Residential	Congested rural population with single phase power line channel
7	Wapda Town	Residential	Urban population
8	Valencia Town	Residential	Urban population
9	Defense Housing Authority	Residential	Urban population

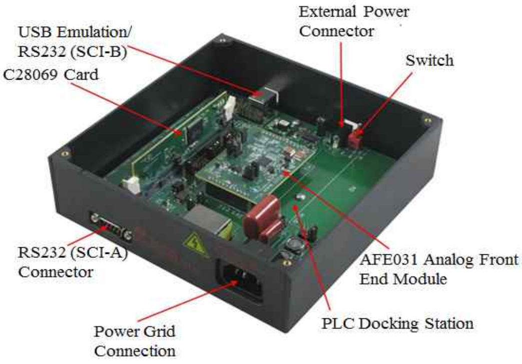


Fig. 3. Transceiver (TMDSPLCKIT-V3) specifications

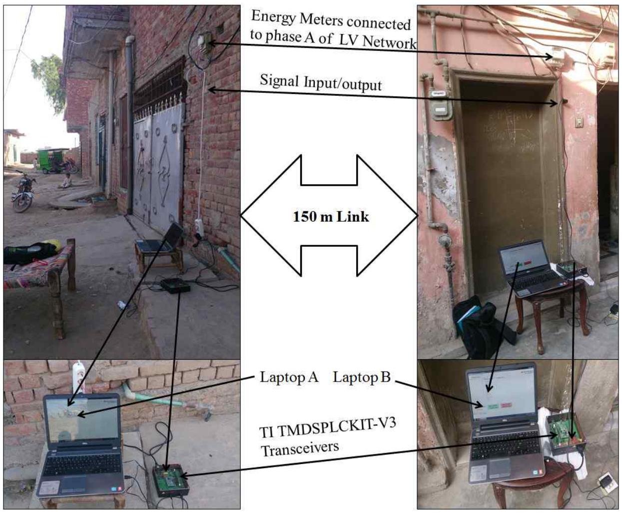
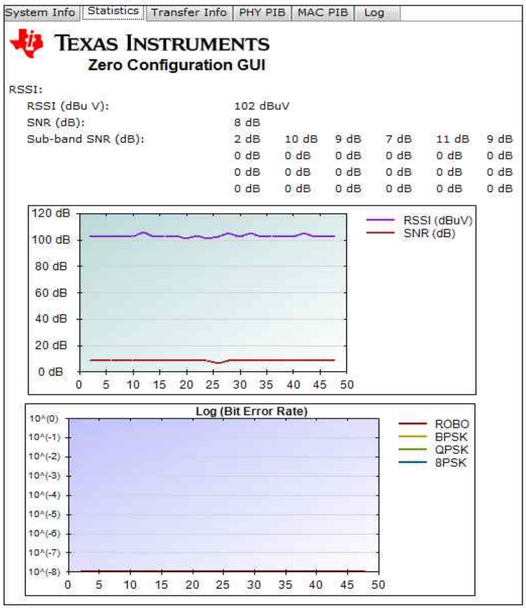


Fig. 4. Field measurement setup

distance 150 m, between each transmitting and receiving end. One volt rms signal is injected through one energy meter and received at another energy meter located 150 m away. The transmission and receiving of signal is accomplished on the same phase that can be any phase such as phase A, B or C. The specifications of transceiver are illustrated in Fig. 3 and experimental setup for field test is shown in Fig. 4 where two laptops connected with PLC transceiver developer kits (TMDSPLCKIT-V3) at two different places, 150 m away from each other. USB Emulation/RS232 (SCI-B) port of transceiver is connected with USB port of each laptop in order to display the transmitted and received results on laptops. Power is supplied to transceivers through external power connector whereas power grid connection port is used to inject the signal into the LV network through energy meters. Data stream is injected from laptop A through energy meter and received at the same phase on Laptop B and vice versa.

The Texas Instruments (TI) transceiver, C2000 power line modem developer kit TMDSPLCKIT-V3 is used for field measurements. AFE daughter card with Texas Instruments integrated powerline communications analog front-end AFE031 is incorporated in TI PLC developer kit.



```
RSSI:
  RSSI (dBu V):          102 dBuV
  SNR (dB):              8 dB
  Sub-band SNR (dB):     2 dB   10 dB   9 dB   7 dB   11 dB   9 dB
                         0 dB   0 dB    0 dB   0 dB   0 dB    0 dB
                         0 dB   0 dB    0 dB   0 dB   0 dB    0 dB
                         0 dB   0 dB    0 dB   0 dB   0 dB    0 dB
```

Fig. 5. GUI of transceiver

Table 3. Experimental results of sites obtained in the field measurements

Sr. No.	Site Name	V_{RX} [mV]	Atten. [dB]
1	Hafeez Center	0.62	-64.14
2	Kot Lakhpat	0.93	-60.57
3	Gaddafi Stadium	1.74	-55.14
4	Ghaziabad	8.34	-41.57
5	Township	10.33	-39.71
6	Lahore Cantt	30.61	-30.28
7	Valencia Town	32.69	-29.71
8	Wapda Town	37.28	-28.57
9	Defense Housing Authority	141.2	-17
10	Average Response	9.18	-40.74

The modem is full G3-PLC and PRIME compliant with software PLC suite, supporting various communication technologies, including OFDM for PRIME, G3-PLC and IEEE-1901.2, it is also SFSK enabled. The G3-PC standard is used in transceiver for field measurements of allocated sites.

The frequency range of transceiver for G3-PLC is 40-90 kHz (CENELEC-A band) for both OFDM and forward error correction (FEC) with data rates up to 46 kbps. The transceiver incorporates the Robust (ROBO) mode, differential binary phase shift keying (DBPSK), differential quadrature phase shift keying (DQPSK) and differential eight phase shift keying (D8PSK) modulation schemes. ROBO mode of transceiver provides repetition code with BPSK.

Analyses of sites include the measurement of parameters like received signal strength and signal to noise ratio (SNR). Fig. 5 is illustrating the statistics of physical test in form of graphical user interface (GUI) of TI showing the received signal strength indicator (RSSI), average and sub-band SNR and bit error rate (BER) of received signal with respect to time.

Narratives of average V_{RX} and attenuation of all selected power line channels during field measurements are tabulated in Table 3. The detailed analysis of attenuation profiles obtained from field measurements is presented in Section 5.

4. Proposed Simulink Model for NB-PLC System

This research work focuses on developing an NB-PLC channel model which is simulated using MATLAB Simulink. The LV distribution network represented in this model is based on the standard network values followed by electric supply companies in Pakistan. The conductor types used in Simulink model for main channel are All Aluminium Conductors (AAC), standard BS-215, code name Wasp and for branches are Polyvinyl Chloride (PVC) copper cable, standard BS-6485 whose electrical parameters are tabulated in Table 4. Fig. 6 illustrates the proposed Simulink model.

The signal is injected in the phase A of LV network between branch 8 and 38 kW RLC load and received on the same phase, at the LV side of 250 kVA transformer using a capacitive coupler to facilitate injection and receiving of communication signal on both the transmitting and receiving ends as shown in Fig. 6. The received signal spectrum is analyzed at spectrum analyzer. The same signal at the same position can be injected in the phases B and C and received in their corresponding same phase. The length of LV distribution lines ranges from 60-150 m. The voltage levels and conductor type of selected LV access network consist of 400 $V_{L\text{-}L}$, 230 $V_{L\text{-}N}$ via 11kV/ 0.4kV transformer, based on AAC, standard BS-215. In this proposed Simulink channel model the length of main channel is 150 m terminated to a 38 kW load with number of branches emanating from it, each of which has 15 m length. A distributed parameter line (DPL) is used to characterize the properties of LV access channel. The parametric values incorporated in DPL and 8 branches are taken from Table 4. A three phase, two winding, 50 Hz transformer is used in the Simulink model that has parametric resistance and inductance of winding 1, 4.32 Ω and 0.45 H respectively whereas winding 2 resistance and inductance are 0.79 Ω and 0.08 H respectively. The transformer has magnetization resistance R_m, 1.8 M Ω and magnetization inductance L_m 500 H, supplied by Y connected three phase, 11 kV source with X/R ratio of 7.

4.1 Impedance modeling for NB-PLC

The importance of various parameters such as G, R, C, L and Z cannot be ignored because the modeling of NB-PLC

Table 4. Electrical parameters of conductors

Conductor Type/Standard	Nominal/ Section Area	No./Nominal diameter of wires	Approximate Overall Diameter	Nominal DC Resistance at 20^{0}C	Current Rating	L	C
	mm^2	No./mm	mm	Ω/km	Amps	µH/m	pF/m
Wasp – BS 215	100	7/4.39	13.17	0.2720	286	0.86	13.6
PVC-BS 6485	14	7/1.60	6.8	1.3030	56	0.59	38

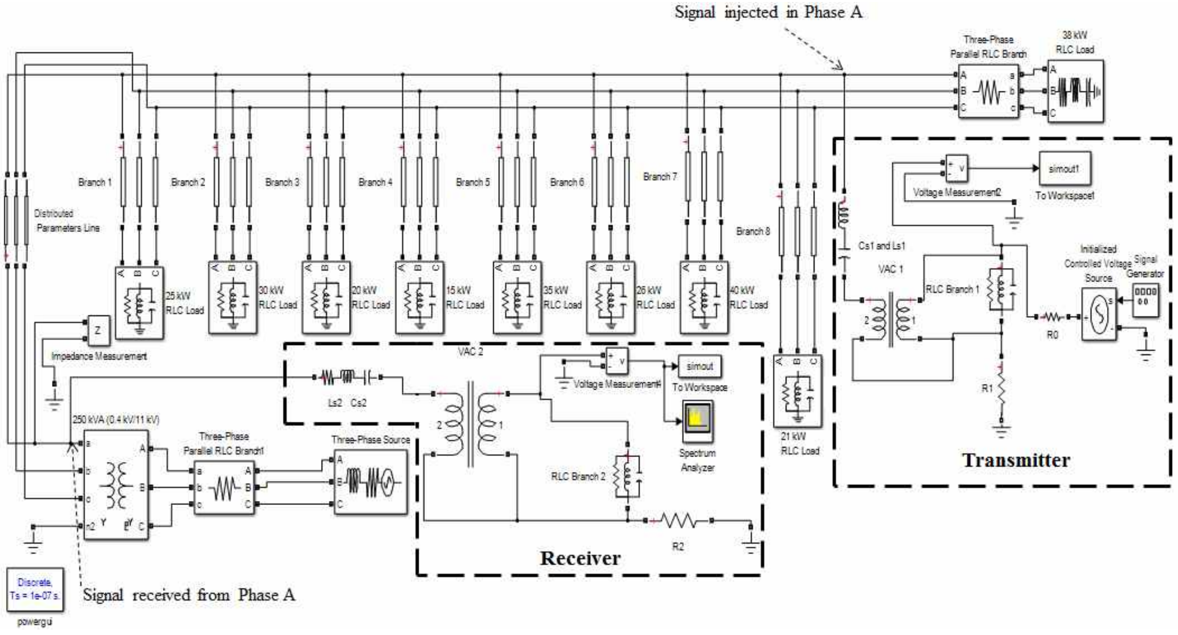


Fig. 6. Proposed Simulink Model

channel is mainly depending on their characteristics. A comprehensive literature for the modeling of various PLC channel parameters is discussed in [14, 19], and [20]. In [14], characteristics of access impedance using NB-PLC are determined by incorporating voltage-current approach. The proposed setup for measurement, presented by authors utilized shunt resistance R_{sh} for the measurement of current, whereas a coupling capacitor in series with parasitic impedance is used to complete the coupling network. The evaluation for the characteristics of impedance is performed by,

$$Z_{a,k} = Z_{m,k} - (R + j\omega L + \frac{1}{j\omega C}) \tag{7}$$

where $Z_{m,k}$ and $Z_{a,k}$ represent the measured impedance and single phase impedance respectively.

$$Z_{a,3-ph} = Z_{m,3-ph} - Z_{3-phase/calibration} \tag{8}$$

where $Z_{a,3\text{-}ph}$ and $Z_{m,3\text{-}ph}$ are phase coupling impedance and measured three phase impedance respectively, whereas $Z_{3\text{-}phase/calibration}$ denotes the calibration impedance of coupling network.

On the other hand, access impedance can be calculated theoretically as,

$$Z_{a,3-ph-theoratical} = \frac{1}{\frac{1}{Z_{a.1}} + \frac{1}{Z_{a.2}} + \frac{1}{Z_{a.3}}} \tag{9}$$

In [19], an indoor PLC channel model is proposed by authors that is focused on the modeling of three types of load impedances, categorized as constant, time varying and frequency selective impedances. Time varying and frequency selective impedances are modeled as,

- Time-varying Impedances:

$$Z_{\omega,t} = Z_{A\omega} + Z_{B\omega} \,|\sin(\frac{2\pi}{T_0} t + \varphi)|; 0 \le t \le T_0 \tag{10}$$

where Z_A, Z_B and ϕ are offset impedance, amplitude of variation and phase respectively.

- Frequency Selective Impedances:

$$Z(\omega) = \frac{R}{1 + jQ(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega})} \tag{11}$$

where R and Q are resistance at resonance and quality factor respectively, whereas ω_0 represents the resonance angular frequency.

Similarly in [20], evaluation of PLC channel by focusing on the properties of access impedance is performed. The analysis depicted in research work includes the noise distribution over NB-PLC frequency range and amplitude responses. A sophisticated measurement tool to investigate the said properties is also proposed. Authors presented four types of models for the modeling of access impedances which are based on various combinations of R, L and C as,

$$Z_S(f) = \frac{1 + 2\pi R_S C_S + (j2\pi f)^2 L_S C_S}{2\pi f C_S} \tag{12}$$

$$Z_P(f) = \frac{R_P + j2\pi f L_P}{1 + 2\pi R_P C_P + (j2\pi f)^2 L_P C_P} \tag{13}$$

By using 12 and 13, type 1 and type 2 can be expressed as,

$$Z_{r1,r2}(f) = \frac{Z_S(f) Z_P(f)}{Z_S(f) + Z_P(f)} \tag{14}$$

However, type3 can be expressed as,

$$Z_{r3}(f) = \frac{Z_{S1}(f) Z_{S2}(f)}{Z_{S1}(f) + Z_{S2}(f)} + Z_P(f) \tag{15}$$

The expression of type 4 is a simplest case of analysis.

After a careful investigation of above mentioned facts, it is worth mentioning that access or line impedances of LV network are one of the key parameters of NB-PLC channel that are used to characterize the behavior of power line which ultimately corresponds to the end consumer/load connected with LV network. The line impedance of NB-PLC channel is usually very small due to the parallel connection of various types of consumers/loads. The small values of line impedances causes the decrease in the magnitude of injected voltage into LV network that affect the performance of NB-PLC [17]. In practical scenarios if magnitude of line impedance is less than 0.5 Ω, the injection of NB-PLC signal within the line will becomes a challenge [22]. On the basis of extensive literature presented in this paper, the frequency selective behavior of domestic loads can be modeled with the help of RLC loads are that is incorporated in the proposed simulation model [20], [23]. In this research work, RLC loads connected with each branch have values, ranges from 20-40 kW in which inductive nature of load is dominating by the ratios of consumed inductive reactive power Q_L and capacitive reactive power Q_C as tabulated in Table 5.

The segregation for the ratios of Q_L and Q_C is done to four classes, depending on the type of measured channels such as worst, bad, good and best. It is analyzed that commercial and industrial consumers fall in the worst class of channel. The reason behind this is the fact that the devices and equipment employed in commercial markets and industry have strong inductive and capacitive characteristics, originated from connected equipment like switch mode power supplies, rectifiers, computers,

Table 5. Active power (W) and reactive power (VAR) ratios of each RLC load connected to LV network

Sr. No.	Active power in watts	Worst channel		Bad channel		Good channel		Best channel	
		Q_C (+VAR)	Q_L (-VAR)	Q_C (+VAR)	Q_L (-VAR)	Q_C (+VAR)	Q_L (-VAR)	Q_C (+VAR)	Q_L (-VAR)
1	25 kW	35	95	30	85	32	68	14	22
2	30 kW	38	99	44	88	25	77	10	26
3	20 kW	33	58	32	42	22	30	8	18
4	15 kW	32	47	29	40	18	26	4	15
5	35 kW	38	100	36	95	24	72	9	23
6	26 kW	35	98	33	90	21	63	7	20
7	40 kW	45	100	41	97	29	68	13	22
8	38 kW	46	95	37	100	27	74	12	24

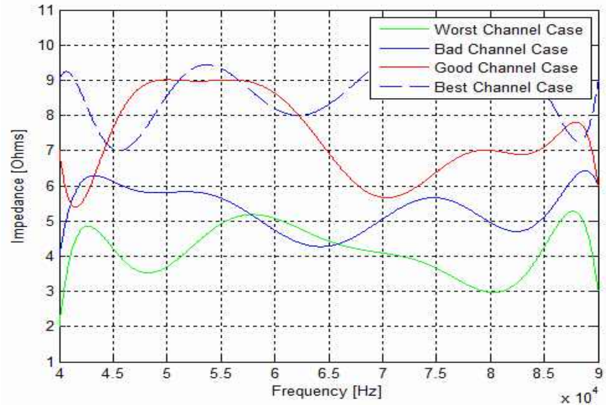


Fig. 7. Line impedance of phase A for worst, bad, good and best channel cases

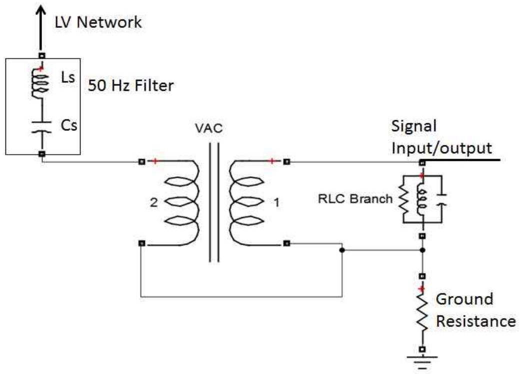


Fig. 8. Schematic of LV phase to ground capacitive coupling device

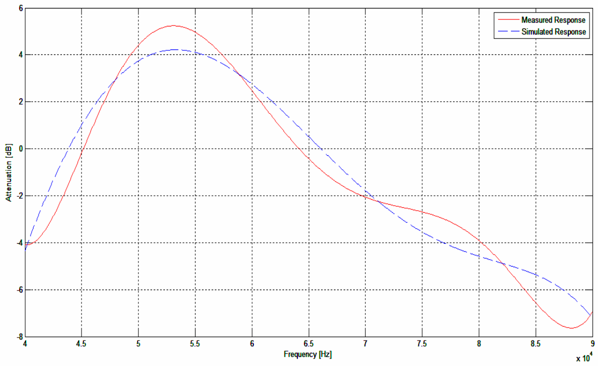


Fig. 9. Measured and simulated Frequency response of capacitive coupling device

induction motors and variable speed drives etc that boosted the inductance within the LV network, whereas capacitor banks for the correction and improvement of power factor of industry and other inductive loads cause the increase in capacitance. Therefore high values of Q_L and Q_C are incorporated in RLC load as tabulated in Table 5. However, bad, good and best classes of channels comprises of residential loads in which bad and good classes of channels have aged LV network infrastructure. The key difference between bad and good classes is: there are narrow streets with small scale industries using embroidery machines and congested population, having poor LV network with a weak O & M system. On the other hand, good class of channels comprises of sophisticated residential societies with good O & M system [24]. Defense Housing Authority (DHA) that is included in best channel category is newly constructed housing society with excellent O & M system for LV network infrastructure. The line impedance of phase A from transformer side is plotted in Fig. 7, after incorporating the parametric values from Table 5 for each worst, bad, good and best channel case. The mean values of line impedances for worst, bad, good and best channels are 3.8 Ω, 5.2 Ω, 7.3 Ω and 8.9 Ω respectively.

4.2 Capacitive coupling device

The capacitive coupling device (CCD) is used to inject the signal in the LV line [12]. A schematic of CCD to inject the signal in phase A of LV network is depicted in Fig. 8. A sinusoidal signal generator gives a 1 V signal to parallel RLC circuit followed by isolation transformer operating on a frequency range 40-90 kHz. Both isolation transformers incorporated at transmitting and receiving, capacitive coupling device are grounded with 1000 Ωresistance.

A 50 Hz filter is introduced at the output of isolation transformer. The model parameters of capacitive coupling device are tabulated in Table 6. The measured and simulated frequency response of capacitive coupling device is shown in Fig. 9. The transceiver coupling interface used at the receiving end has same values as the capacitive

Table 6. Model parameters of capacitive coupling device

LV Series L_s C_s parameters		RLC Branch parameters			Isolation Transformer		
L_S [μH]	C_S [nF]	R_P [kΩ]	L_P [μH]	C_P [nF]	Turn Ratio	Magnetization Resistance, R_M [Ω]	Inductance, L_T [μH]
47	100	25	135	14	1:1	50	400

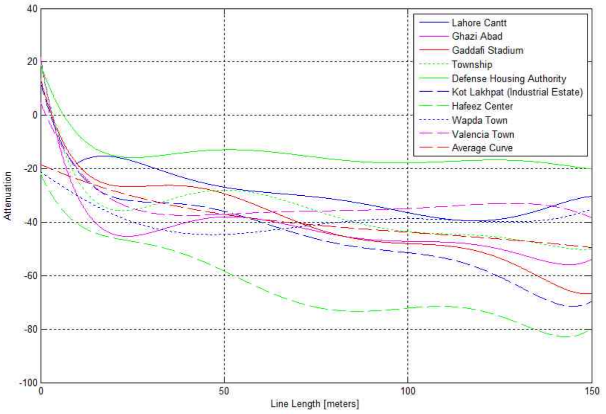


Fig. 10. Simulation of field measurement results for all sites versus line length

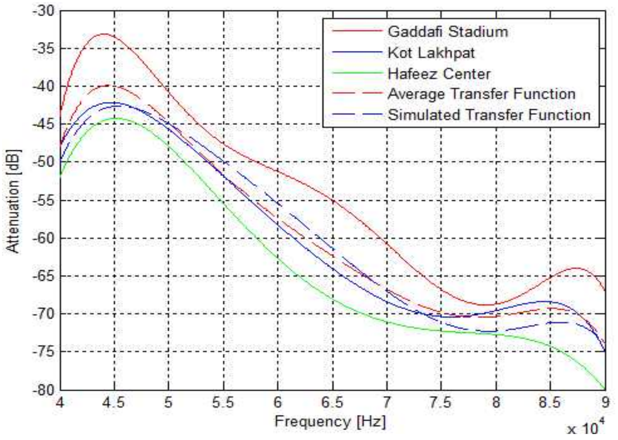


Fig. 11. Worst case of NB-PLC channels with comparison of Average and Simulated transfer functions

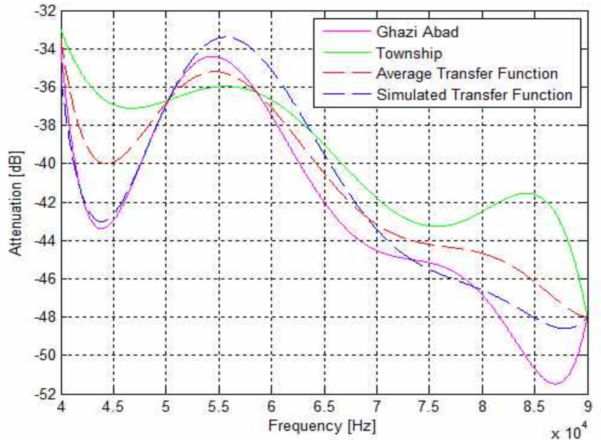


Fig. 12. Bad case of NB-PLC channels with comparison of Average and Simulated transfer functions

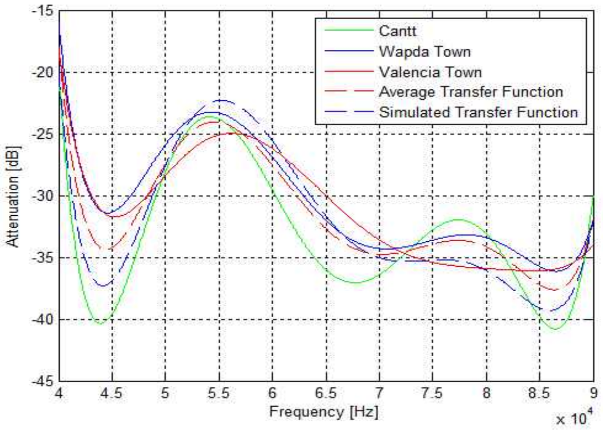


Fig. 13. Good case of NB-PLC channels with comparison of Average and Simulated transfer functions

coupler of transmitter side. The transfer function plots of proposed Simulink model by injecting the signal through capacitive coupling device are discussed in the following Section.

5. Results and Discussion

Field trials and measurements of all allocated sites in Lahore were carried out. Detailed analyses of site measurements with respect to the line length presented in Fig. 10 reveal the fact that attenuation increases with the increase in the length of channel. Hafeez center, Kot Lakhpat and Gaddafi Stadium offer the worst PLC channel where the attenuation dropped down to -80 dB whereas DHA Phase-V provides the best PLC channel with -16 dB mean signal's attenuation due to its newly installed power distribution network. The densely populated rural areas of Ghaziabad and Township which mainly comprise of narrow street and bazaars exhibited bad PLC channel with the attenuation varied between -33 to -50 dB. However big residential societies like Wapda Town, Valencia Town and Lahore Cantt offered good PLC channel with mean attenuation -29.52 dB. The average curve shown in Fig. 10 represents the fact that the average power line channel attenuations of all sites lie in the range -20 to -49 dB.

After considering all the discussion mentioned above, NB-PLC channels are classified into 4 categories such as worst, bad, good and best classes of channels. Figs. 11 to 14 illustrate the TFs of all four classes of NB-PLC channels. The average measured and simulated TFs of five

Table 7. Average, measured and simulated Transfer Functions of worst, bad, good and best channel cases

Sr. No.	Channel Class	Average Measured Transfer Function	Average Simulated Transfer Function
1	Worst Case	-59.95 dB	-58.54 dB
2	Bad Case	-40.64 dB	-41.22 dB
3	Good Case	-29.52 dB	-30.85 dB
4	Best Case	-18.28 dB	-18.15 dB

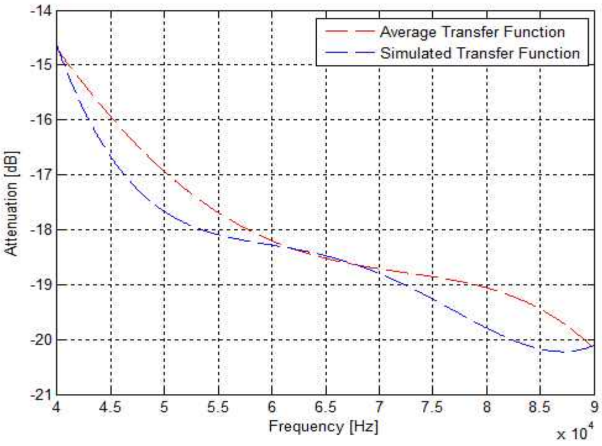


Fig. 14. Best case of NB-PLC channels with comparison of Average and Simulated transfer functions

sites which are classified as worst and bad channels are depicted in Figs. 11 and 12. The worst and bad classes of NB-PLC channels exhibited the variations in attenuation profiles between -38 to -73 dB and -35 to -48 dB respectively.

However, good and best classes of NB-PLC channels are shown in Figs. 13 and 14 in which good case caters the three properly planned residential societies with average TFs between -20 dB to -37 dB and best case encounters the attenuation profile of DHA between -15 dB to -20 dB. Comparison of average attenuation profiles achieved from both measure and simulated TFs is tabulated in Table 7, which shows that the average TF values of each worst, bad, good and best class of NB-PLC channels for both measured and simulated values are close enough to fairly validate the proposed model. Furthermore, it is evident from the results shown in Figs. 11 to 14 that average measured and proposed Simulink model TFs are in good agreement with each other thus validating the proposed Simulation model [24].

6. Conclusions

This paper presented the extensive field measurements for the characterization of LV NB-PLC channel of various sites of Lahore city. The evaluated sites for NB-PLC channel cater all possible types of loads and channel characteristics. After a careful comparison on various NB-PLC studies available in literature, state of the art Simulink model is proposed that has been verified by comparing its results with measured results of NB-PLC channels. A complete LV network model is developed in Simulink that can analyze all kinds of NB-PLC channels. The parametric values of LV network that mainly encompass conductor/ cable parameters and various types of impedances can be rearranged with respect to design requirements. Impedances are designed sophisticatedly by using RLC loads. The proposed model is based on a real case study that incorporates actual parametric values of installed LV network in Lahore city. The NB-PLC signal is injected into LV network with the help of modeled CCD whose frequency response is also presented in this paper. The allocated sites for the field measurements are segregated into four classes (worst, bad, good and best) with respect to their NB-PLC channel characteristics. Average measured and simulated TFs of all evaluated sites are compared and discussed in detail which is close enough to validate the proposed model. The Simulink model can play an effective role in order to examine the performance and characteristics of any LV NB-PLC channel model in the perspective of AMI.

References

[1] B. Masood and S. Baig, “Standardization and deployment scenario of next generation NB-PLC technologies,” *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 1033-1047, 2016.

[2] B. Masood, S. Baig, and A. ur Rehman Raza, “Opportunities and Challenges of ICT in AMI,” *World Applied Sciences Journal*, vol. 23, no. 3, pp. 435-443, 2013.

[3] T.-E. Sung, A. Scaglione, and S. Galli, “Time-Varying Power Line Block Transmission Models over Doubly Selective Channels,” *in IEEE International Symposium on Power Line Communications and Its Applications*, 2008.

[4] T. Banwell and S. Galli, “A Novel Approach to the Modeling of the Indoor Power Line Channel Part I: Circuit analysis and Companion Model,” *IEEE Transactions on Power Delivery*, vol. 20, no. 2, 2005.

[5] S. Galli and T. Banwell, “A novel approach to the modeling of the indoor power line channel part II: Transfern function and its properties,” *IEEE Transactions on Power Delivery*, vol. 20, no. 3, 2005.

[6] J. Anatory, N. Theethayi, and R. Thottappillil, “Power-Line Communication Channel Model for Interconnected Networks Part I: Two-Conductor System,” *IEEE Transactionson Power Delivery*, vol. 24, no. 1, 2009.

[7] J. Anatory, N. Theethayi, and R. Thottappillil, “Power-Line Communication Channel Model for

Interconnected Networks Part II: Multiconductor System," *IEEE Transactions on Power Delivery*, vol. 24, no. 1, 2009.

[8] M. Zimmermann and K. Dostert, "A Multipath Model for the Powerline Channel," *IEEE Transactions on Communications*, vol. 50, no. 4, 2002.

[9] A. M. Tonello and F. Versolatto, "Bottom-Up Statistical PLC Channel Modeling Part I: Random Topology Model and Efficient Transfer Function Computation," *IEEE Transactions on Power Delivery*, vol. 26, no. 2, 2011.

[10] A. M. Tonello and F. Versolatto, "Bottom-Up Statistical PLC Channel Modeling Part II: Inferring the Statistics," *IEEE transactions on Power Delivery*, vol. 25, no. 4, pp. 2356-2363, 2010.

[11] A. M. Tonello and F. Versolatto, "New Results on Topdown and Bottom-up Statistical PLC Channel Modeling," in Third workshop on Power Line Communications, 2009.

[12] A. Cataliotti, V. Cosentino, D. D. Cara, and G. Tin'e, "Measurement issues for the characterization of medium voltage grids communications," *IEEE transactions on instrumentation and measurement*, vol. 62, no. 8, 2013.

[13] A. Cataliotti, D. D. Cara, R. Fiorelli, and G. Tin, "Power-Line Communication in Medium-Voltage System: Simulation Model and Onfield Experimental Tests," *IEEE transactions on power delivery*, vol. 27, no. 1, 2012.

[14] G. Chu, J. Li, and W. Liu, "Narrow Band Power Line Channel Characteristics for Low Voltage Access Network in China," *in IEEE 17th International Symposium on Power Line Communications and Its Applications*, 2013.

[15] A. Cataliotti, V. Cosentino, D. D. Cara, and G. Tin, "Simulation and Laboratory Experimental Tests of a Line to Shield Medium-Voltage Power-Line Communication System," *IEEE transactions on power delivery*, vol. 26, no. 4, p. 2011, 2011.

[16] W. L. Martin Sigle and K. Dostert, "On the Impedance of the Low-Voltage Distribution Grid at Frequencies Up to 500 kHz," *in IEEE International Symposium on Power Line Communications and Its Applications*, 2012.

[17] I. H. Kim, W. Kim, and B. Park, "Channel measurements and field tests of Narrowband Power Line Communication over Korean underground LV Power Lines," *in 18th IEEE International Symposium on Power Line Communications and Its Applications*, 2014.

[18] M. Antoniali and A. M. Tonello, "Measurement and characterization of load impedances in home Power Line Grids," *IEEE transactions on instrumentation and measurement*, vol. 63, no. 8, pp. 548-556, 2014.

[19] F. J. C. ete, J. A. Corts, L. Dez, and J. T. Entrambasaguas, "A channel model proposal for indoor Power Line Communications," *IEEE Communications Magazine*, 2011.

[20] J. Bausch, T. Kistner, M. Babic, and K. Dostert, "Characteristics of indoor power line channels in the frequency range 50-500 kHz," *in IEEE International Symposium on Power Line Communications and Its Applications*, 2006.

[21] B. Masood and S. Baig, "Channel Modeling of NB-PLC for Smart Grid," *in IEEE Symposium on Computers and Communications* (*ISCC*), 2015.

[22] J. N. Hendrik C. Ferreira, Lutz Lampe and T. G. Swart, Power Line Communication: Theory and Applications for Narrowband and Broadband Communications over Power Lines. John Willey & Sons, 2010.

[23] A. M. Pasdar, I. H. Cavdar, and Y. Sozer, "Power-Line Impedance Estimation at FCC Band Based on Intelligent Home Appliances Status Detection Algorithm Through Their Individual Energy and Impedance Signatures," *IEEE transactions on Power Deliver*, vol. 29, no. 3, pp. 1407-1416, 2014.

[24] Bilal Masood, Muhammad Usman, Muhammad Usman Gul and Waheed Aftab Khan, "Measurements and Characterization of Power Transformer and Low Voltage Access Network for NB-PLC," *in International Journal of Communication Systems, Wiley*, 2017, DOI: 10.1002/dac.3344.

Bilal Masood was born in Lahore, Pakistan, in 1984. He received BS and MS in Electrical Engineering from The University of Lahore, Lahore, Pakistan in 2008 and 2010 respectively. He has completed his PhD degree in Electrical Engineering from COMSATS Institute of Information Technology, Lahore, Pakistan. His research interests include opportunities and challenges of ICT in Smart Grid. Currently, he is working as an Assistant Professor at Superior University, Lahore, Pakistan.

Manzoor Ellahi is serving as Lecturer in Superior Group of Colleges. He completed his B.Sc. (Electrical Engineering) from University of Engineering & Technology, Lahore Pakistan and MS (Electrical Engineering) from University of Lahore, Pakistan. He is currently perusing his Ph. D (Electrical Engineering) from University of Lahore, Pakistan. His research interests are Power System Protection, HVDC transmission systems and Energy conservation Techniques.

Waheed A. Khan is serving as Lecturer in Superior Group of Colleges. He completed his B.Sc. (Electrical Engineering) from University of Engineering & Technology, Lahore Pakistan and MS (Electrical Engineering) from University of Lahore, Pakistan. He is currently perusing his Ph. D (Electrical Engineering) from Superior Group of Colleges. His research interests are Power System Protection, HVDC transmission systems and Smart Energy Systems.

Waqar Akram received BSEE from the The Superior College, University Campus Lahore, Pakistan in 2015. Currently he is pursuing MSEE from the same university. His research interests include power system analysis.

Muhammad Usman has completed his Masters of Science in Electronics and Electrical systems and Bachelors of Sciences in Electrical Engineering from The University of Lahore, Pakistan. He is interested in the contemporary progress in Pakistan and technological solutions in energy sector to overcome energy crisis. Currently serving The University of Lahore, Lahore Pakistan for mentoring student's in the field of Electrical Engineering and Technology.

Muhammad Talha Gul was born on April 18, 1984, in Pakistan. He received the B.S. of Electrical Engineering with (Hons) from the University of Engineering and Technology, Peshawar, KPK, Pakistan, in 2007. He received the MBA Master of Business Administration in Human Resource Management (HRM) from the Jinnah Institute of Technology, Pakistan in 2010 and also the M.S. degree in Electrical Engineering (Signal Processing and Wave Propagation) from the Linnaeus University, Vaxjo, Sweden in 2012. He has completed the Ph.D. degree in Electronic Engineering at Kyung Hee University, South Korea. His research interests include Area of Millimeter-wave Circuit Design, Power Management IC Design, Image sensors and Analog Integrated Circuit Design. Currently, he is working as an Assistant Professor and Chairman, Electrical Engineering Department at Superior University, Lahore, Pakistan.