An In-Depth Study on Power Line Communications

by

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B.Tech, Guru Nanak Dev University, 2016

Project Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Engineering

in the
School of Engineering Science
Faculty of Applied Sciences

Simon Fraser University
Summer 2018

Approval

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Date Defended/Approved: 13th April, 2018

Abstract

Power Line Communication has acquired tremendous interest from the research community since its applications and development in the field of Smart grid, in-home & vehicular communication, and its role in Internet of Things (IoT). In this project, I study the features of power line communication and provide an overview of applications in both narrowband and broadband systems, listing applicable standards and specifications. We study the problems in the technology and how recent developments have led to resolve them. A number of tests were conducted for the in-home Power Line Communication (PLC) setup, and different PLC modules were tested for a variety of wiring systems. Further, we conducted tests on two transformers to list the frequencies that can pass through the system, and to study general behaviour of the system to high frequencies.

Keywords: Power Line Communication; In Home PLC; Transformer; Low Voltage (LV); Broad Band PLC (BB PLC); Narrow Band PLC (NB PLC)

Acknowledgements

I would like to take this opportunity to thank my supervisor, Dr. Ash M. Parameswaran for giving me an opportunity to work on the project under his supervision. I would also like to thank my project instructor Mr. Balbir Gill for his ideas and, full guidance and support during the project. I would like to express my gratitude towards Dr. Ali Palizban, PhD, P.Eng; Program Head of Electrical Power and Industrial Control at British Columbia Institute of Technology, for his great support to run the experimentation in the Data Communications and Networks Laboratory at the British Columbia Institute of Technology (BCIT). Lastly, I would like to thank Mr. Amritpal Singh for his willingness to help me understand the electrical wiring systems and their design. I appreciate everyone who has directly or indirectly contributed towards the project.

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List of Acronyms

ARIB	Association of Radio Industries and Businesses
BPSK	Binary Phase Shift Keying
CENELAC	European Committees for Electrotechnical Standardization
CSMA-CA	Carrier Sensing Multiple Access with Collision Avoidance
DQPSK	Differential Quadrature Phase Shift Keying
FCC	Federal Communications Commission
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
LV	Low Voltage
MV	Medium Voltage
OFDM	Orthogonal Frequency Division multiplexing
PLC	Power Line Communication
QAM	Quadrature Amplitude Modulation
TDMA	Time Division Multiple Access

Chapter 1.

Introduction

Power Line Communication has been examined for a long time. Power Line Communication (PLC) involves the transfer of data signals over standard household electrical wires and cables. We can use the existing power cables to transmit both power and data signals over a shared power system. The basic principle of operation of this system is the addition of a modulated carrier signal to the electrical signal around a carrier frequency. The electric current and data signals vibrate at different frequencies, and they do not interfere high enough to disrupt the data transmission over the powerline network. The PLC technology varies from being limited to a single building to crossing different networks. The data rates and the distance limits depend and vary according to different power line communication standards.

The first PLC systems, named Ripple control, were developed on low and medium voltage electrical networks in 1950, with a carrier frequency ranging between 100 Hz and 1 KHz [3]. Pulsadis was the first industrial system that came into being in 1960. One of the systems to follow the Pulsadis was the system that used CENELAC band (frequency ranging from 3 kHz to 148.5 kHz) [3]. Both the systems allowed two-way communication on low voltage (LV) electrical cables.

PLC has found a large number of applications in the real world in the past few decades and is continuing to make strides in broadband multimedia applications. It has made a vital space of its own with a high grade of usage in in-home (or intranet) communication or for low voltage applications. It is being considered as a low cost alternative to complement the existing technology for wider connection coverage. Some applications include the detection of the network status online and monitoring it regularly & controlling equipment [1]. The main advantage of it being that new cabling is not required and can thus be very well used to enhance the applications of Smart Grid, in-home automation and telemetry [2]. PLC has also been found of use in transport systems such as, in-vehicle serial communication, naval and aircraft systems, and in trains [2]. Since the application is on electrical cables, the modules operate with different security protocols (eg. Use of network & default encryption keys) and cannot be intercepted by any wireless tapping. Many novel propositions are being proposed every day in the areas of - robotics, authentication, contactless communication, and wireless power transfer being a few of them [2]. An aggressive research is being conducted in the field of Smart grid as it has the possibility of reducing carbon dioxide emissions by a great deal [4]. Real time measurement, monitoring and control of transmission, generation and distribution networks are important factors in the success of the Smart Grid technology, which will be provided by the PLC [4].

Chapter 2.

Background Knowledge

2.1. Classification of PLC

Power Line Communication can be divided into two main categories:

i) Narrow Band PLC ii) Broad Band PLC

- **Narrow Band PLC:**

This type of Power Line Communication generally refers to the communication occurring over the frequency range of 3 kHz to 500 kHz, that is, the CENELAC (European norms) / ARIB (Japanese norms) / FCC (USA norms) bands [2]. These systems can be further divided into Low data rate and High data rate systems. LDR systems provide data rates of up to a few kilobytes per second (kbps), and ranging from a hundreds of kilobytes to 1 Megabyte per second (Mbps) in HDR systems.

- **Broad Band PLC:**

The BB PLC (Broad band Power line communication) is a branch of PLC that allows the transmission of high-speed data over a wider frequency range. It uses the frequency band of 1.6 MHz to 30 MHz [2]. Products manufactured for BB PLC allow data rates up to 500 Mbps. Due to higher signal frequencies and the asymmetries in the power line networks, radiated emissions are a very big concern in BB PLC. Specifications have been laid out to standardize the acceptable radiation mission limits.

2.2. Network Topologies

This section distributes the electrical network as per the voltage levels. The communication over the power line network greatly varies according to the operation voltages of the power lines. The distribution topology may differ form country to country.

- High Voltage (HV) Lines: The powerlines with voltages in the range form 110kV to 380 kV are used for long distance transmission of electricity. These are overhead lines of approximately 100 km in length, with no or very little branching. Due to this factor, it can serve as a very good communication channel for PLC as it has very less attenuation per line length [4]. But it has not been put into very large-scale use due to noise and reflection issues, and high cost of coupling the communication signals in and out. There have been successful trials using the HV lines too as there is minimum branching in these networks [13].

- Medium Voltage (MV) Lines: These lines conduct voltages in the range 10kV to 30kV. These are used for distribution to urban and rural substations and are connected to the high voltage lines through transformers. PLC has been realised on MV network as well. A variety of experimentation has been conducted to conclude the issues and results of using MV lines for PLC [1], [14].

- Low Voltage (LV) Lines: These are the lines that supply electricity to the consumers with a capacity of 110V to 400V, connected to the MV Lines through a secondary transformer substation. LV lines run from the distribution board to the various power sockets in every room of the house. The in home low voltage network is the most exploited one for the power line communication system. Coupling devices are used to transfer the signal through LV/MV transformers.

2.3. Standards

This section deals with some of the numerous industry specifications of the NB and BB PLC.

- NB PLC: The Low Data Rate (LDR) systems have throughputs of a few kilobits and are based on single carrier technology [4]. The standards, given in detail below, are based on all the layers of the open systems interconnection (OSI) model. Not only has it found the main application in industrial and building automation, it also has the quality of being used on media other than the power line systems. Some standards given by the NIST Smart Grid Interoperability Panel (SGIP) Catalog of standards are: Konnex EN50090, EN13321-1, ISO/IEC 14543-3, X10, HomePlug C&C, and more [4]. A wave of activity has been taken place to develop NB PLC for relatively high data rate transmission [2]. We mainly focus on the physical layer (PHY) of the HDR NB-PLC. Some of the specifications are detailed below:

i. PRIME (PowerLine Intelligent Metering Evolution) ITU – T G9903 is an interoperable standard developed by the PRIME alliance [6]. It works in CENELAC A band. It uses OFDM subcarriers and it also deploys various modulation techniques, including differential binary, quaternary and eight phase shift keying (DBPSK, DQPSK, D8PSK) [4]. It has been developed for the purpose of communication for smart metering. It provides scalable data rates up to 128.6 kbps [5]. It uses both contention based CSMA/CA and contention free TDMA mechanisms for access the channel [4].

ii. G3-PLC ITU – T G9903 has been developed by the G3-PLC Alliance. It is almost similar to PRIME with certain additions to the techniques set up in the former for more robust system output. G3 PLC works on CENELAC, ARIB and FCC bands, ranging from 10 kHz to 490 kHz [8]. It also uses OFDM subcarriers and uses DBPSK and DQPSK with an additional outer Reed-Solomon convolutional coding for Forward error correction [2] [4]. It provides scalable data rates up to 250 kbps and uses MAC based CSMA mechanism for channel access. In addition to providing communication to smart metering, it also contributes in automation, lighting, and energy management systems. 6LoWPAN adaptation layer is incorporated to transmit IPv6 packets over the power line channels [8].

iii. IEEE P1901.2 is a PLC standard for both AC and DC lines. It operates on CENELAC A, B, C, D, and FCC bands, frequencies below 500 kHz. It is applicable to both low voltage indoor/outdoor, as well as medium voltage in both urban and long distance rural communications. “This standard addresses grid to utility meter, grid automation, electric vehicle to charging station, and within home area networking communication scenarios. Lighting and solar panel PLC are also potential uses of this standard” [9]. Some amendments to this ratification made in 2013 have been drafted in [10] for incorporation of some clarifications and corrections related to the interleaver design, modifications to the frame counter size for security and more.

iv. ITU – T G.hnem also works on CENELAC A, B, C, D, and FCC bands. It uses windowed OFDM subcarriers and also uses QPSK and 2-4-16-QAM modulation techniques, providing data rates up to 1 Mbps. It also uses additional Reed-Solomon convolutional coding and repetition coding and interleaving. The coexistence of IEEE 1901.2 and G.hnem is still in question because of some issues.

❖ BB PLC: The PLC community started developing BB PLC solutions for the access and in-home domains in the late 90’s. Main alliances such as Home socket Power Alliance, Universal Power Alliance (UPA), and the High definition Power Line Communication alliance (HD-PLC) gave out a number of specifications. Following is a list of some of the vendors and the technologies they manufactured: Powerhouse Thomson (X10); Yitran, Renesas, Ariane Controls (HomePlug CC); Renesas (Echelon); Intellon, Devolo, Motorola, Linksys (HomePlug AV); DS2, Corinex, Netgear (UPA); and Panasonic (CEPCA) [3]. The data rates varied from 3.8 Mbps to 540 Mbps [3]. Since most of them are not interoperable, IEEE P1901 and ITU-T started the consolidation of the BB PLC Systems in June 2005 and April 2006, respectively, changing the PHY layer and overall architecture.

i. IEEE 1901 was published by the IEEE P1901 Corporate Standards Working Group, based on the Huawei proposed IoT solution. It works in the frequency ranging from 2 MHz up to 50 MHz. The standards have been developed for High Speed Home area networks and Access Networks. The physical layer uses Wavelet OFDM using bit-loading up to 4096-QAM and the MAC layer uses TDMA-CSMA/CA channel access modes [4].

ii. ITU – T G.hn, developed by the ITU – T uses scalable frequency bandwidth from 2 MHz up to 100 MHz, with three different and interoperable bands. The architecture is similar for both IEEE 1901 and ITU –T G.hn, with different naming criteria for the network components in the two standards [4]. From the study of literature standards, we find that it makes use of OFDM modulation technique with a bit-loading of up to 4096-QAM. It uses LDPC (Low Density Parity Check) error correcting code and allows data rate ranging from 200 Mbps to 1Gbps. The channel access modes used are TDMA-CSMA/CA.

iii. HomePlug: The HomePlug AV2 specification, designed for in-home communication adapted to the power line channel, was released in 2012 that includes Multi-Input Multi-Output (MIMO) with beamforming, extended frequency range of up to 86 MHz. It has been established for use within Smart Grid Applications. It also uses OFDM and up to 1024/4096 QAM modulation techniques. The HomePlug AV and AV2 allow data rates up to 1 Gbps and are interoperable with each other. Convolutional and Turbo codes are the error correction codes used in the standard. HomePlug AV2 has complete operability with HomePlug AV and HomePlug Green PHY devices [16]. HomePlug technology specifications offer the market a broadband solution with HomePlug AV, high bandwidth solution with HomePlug AV2, and smart home solution with HomePlug Green PHY [16]. “On the MAC layer HomePlug AV provides a Quality of Service connection oriented, contention-free service on a periodic TDMA allocation and a connectionless, prioritised contention-based service on CSMA/CA allocation” [15].

The commercial HomePlug AV module designed by The HomePlug Power-Line Alliance [16] allows you to simply socket in and connect to the internet. It has been designed to transmit High Definition Television (HDTV) and Voice over Internet Protocol (VoIP) around home, without noticeable dropouts. It has the quality of being in Active, Standby and Idle power saving modes.

Given below, is the summary of standardization bodies for BB PLC.

Table 1 Standardization Bodies for BB PLC [3]

Technologies or standards	**Industrial consortium**	**Technologies**
HOMEPLUG	CONSORTIUM HOMEPLUG (US) Leader: INTELLON	HomePlug 1.0, Turbo (throughput of 14 & 85 Mbps) HomePlugAV (throughput 200M) Technology: OFDM, up to 1024/4096 QAM, TDMA-CSMA/CA
UPA	Consortium UPA(EU) Leader: DS2	UPA (throughput of 45 Mbps) UPA HD (throughput 200M) Technology: OFDM, CSMA/CA
CEPCA	CONSORTIUM CEPCA (Japan) Leader: Panasonic	HD-PLC (throughput 220M) Technology: wavelets, TDMA
IEEE	IEEE P1901 WG	Draft standard based on HomePlug AV

2.4. Literature Review

HomePlug AV and HomePlug AV2 specifications can connect devices such as Smart TVs and HD media players to the Internet by establishing a connection to the home router as well as the coverage of existing Wi-Fi network can also be enhanced [16]. Authors in [3] have explained in detail the different types of in-home PLC technologies and the standards through which they show acceptable functioning behaviour. The in-home

Broadband PLC market is significantly. The User domain advantages include home automation and control and Internet access [2]. For BB PLC systems, where there are very high signal frequencies, the signals have shorter wavelengths as compared to the length of the power lines, which results in electromagnetic radiation [2]. PLC systems are, thus, subject to regulations that limit the strength of the signals coupled into the power lines. The construction quality of the power strip has a great influence on its attenuation. Therefore, we should avoid connecting PLC devices to the power strip [12].

Authors in [1] simulate and experiment a complete model of the NB PLC communication scenario in an MV network and find it feasible to exploit the medium voltage network as ideal for PLC. They transmit the signal between two distribution transformers over an MV network with 24kV mains voltage. The evolution of PLC lies in using both the narrowband and broadband frequency spectrums for PLC signal transmission in Smart Grid [7]. PLC has a very important role to play in the user as well as distribution domain of the Smart Grid network. Some of the services include, monitoring and control of the power signal; energy management; and smart metering for demand response and dynamic pricing [2][7]. Coupling plays an important role in injection and extraction of data communication signals into or from power lines [11].

The distribution transformers are found in secondary substations, and connect the transmission grid to the distribution grid in Smart Grid. There have been recommendations for using the PLC technology over the High Voltage Lines and many successful tests have been conducted as well. The communication channel is difficult to model as the impedance of the wiring keeps changing very frequently as the devices are constantly being connected or disconnected from the electrical wiring [12]. The authors in [13] find reflection, occurring due to inconsistent impedance changes, and noise as limiting factors to PLC over High Voltage lines. Weather affects the PLC HV channel as it can increase or decrease the channel attenuation [13].

Chapter 3.

Experimental setups and Results

3.1. In Home PLC setup

General PLC setup: Two modules (based on HomePlug AV), manufactured by D-Link®, were tested for the purpose of understanding and testing the technology. The adapter of the module (Module 1) is plugged into an AC wall outlet near the router. An Ethernet Cable is connected to the network cable connector located on the bottom of the adapter and the other end is connected to the router of our existing Internet system. The switch is connected to any other wall outlet in any location of the same wiring system and an Ethernet wire connects the switch to our device. The picture shown below is an example setup made for the testing.

Figure 1 Module 1 Setup

For the wireless module (Module 2), the Switch is replaced with the wireless adapter and the devices are connected to the network by setting up the system using the Wi-Fi Configuration Card supplied with the system.

Figure 2 Module 2 Setup

Module Descriptions are as follows:

❖ **Module 1**: PowerLine AV 500 4-Port Gigabit Switch Kit

The module includes:

- One PowerLine AV 500 Adapter (DHP-502 AV)
- One PowerLine AV 500 4- Port Gigabit Switch (DHP-540)
- Two Ethernet Cables
- Power Cable (for DHP-540 Switch)

Module Specifications:

- HomePlug AV standards
- Compatible with IEEE 1901
- Maximum PHY Rate – 500 Mbps
- Power line Frequency band – 2MHz to 70 MHz QoS
- 128 bit AES encryption
- 110 ~ 240V AC, 50/60 Hz Power Input
- Push & Secure encryption button
- Plug & Play installation

- **Module 2**: PowerLine AV 500 Wireless Extender Kit (DHP-W311AV)

The module includes:

- One PowerLine 500 Mini Adapter (DHP-308 AV)
- One PowerLine 500 Wireless Extender (DHP-W310AV)
- Two Ethernet Cables

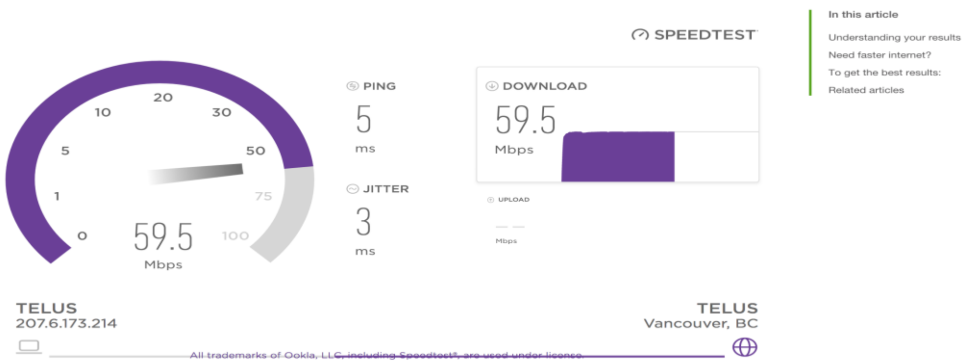
Module Specifications:

- HomePlug AV standards
- Compatible with IEEE 1901
- Maximum PHY Rate – 500 Mbps
- Power line Frequency band – 2MHz to 30 MHz
- 128 bit AES encryption
- 100V ~ 240V AC, 50/60 Hz Power Input
- Push & Secure encryption button
- Plug & Play installation

The specifications of the modules, given above, were obtained from the manuals available with the device. Testing Scenarios were based on different electrical wiring systems.

3.1.1 House#1:

This house was built in the late 1980's with the wiring system according to the electrical code at that time. The sockets on which the tests are conducted are all 3-prong sockets. The wiring is all Aluminium based. In this type of wiring system, there is no dedicated socket as every socket has a shared connection with some load. In the basement of house, after some renovation, two dedicated sockets (Socket a, b) were added. All the remaining sockets have shared loads. Speed test results show the difference between the two. The figure below shows a part of the wiring blueprint of the house. The electrical panel allows 120~208 V AC voltage. The household uses Internet plan by TELUS with theoretical promise of giving a data rate of 75 Mbps. The test was conducted during the day, between 12:00 to 14:50 hr. The speed of the connection is measured using the TELUS and SHAW Speed Test feature available on their website.



The blueprint has been designed in the software named, Microsoft Visio professional. The sockets have been numbered for our convenience, as we set our adapter and switch at different points. The blueprint shows three different rooms on the main floor and three in the basement.

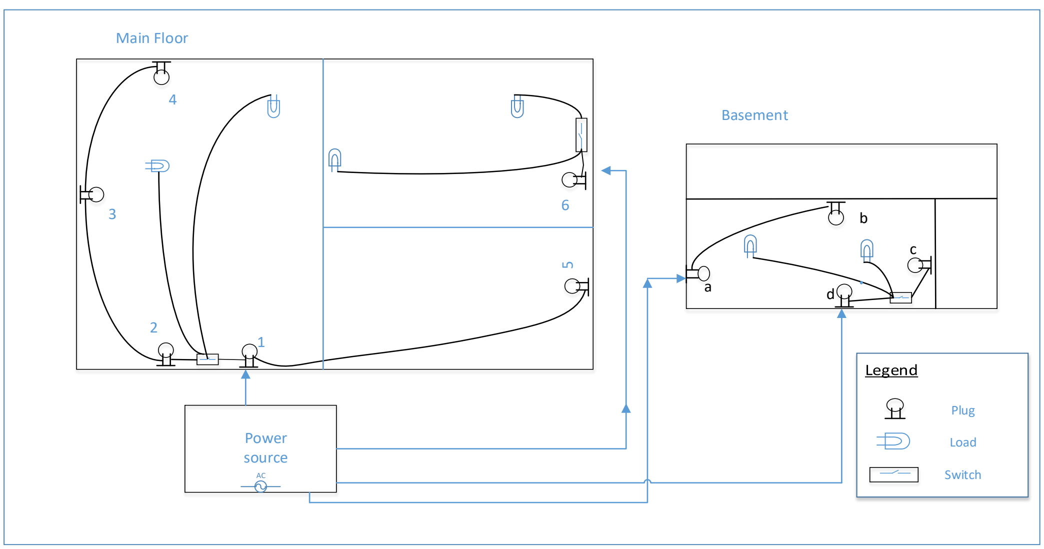


Figure 3 Wiring Blueprint - House# 1

We take into consideration, different scenarios to test the system to see the effect of different loads and interferences. Both the modules were tested to measure the speed of the network.

i. Scenario 1: 502 AV/308 AV Adapter at socket 1, which has a heavy load connected on it, namely the IPTV, Speakers and router. The 540 Switch/W310 AV extender is connected on Socket 3, which just has lighting and plugging load. We connect our laptop via Ethernet Cable to the switch / wirelessly (for module 2) to measure the speed using the TELUS Speed Test feature available on their website. The two modules are in the same room but different sockets.

Table 2 Data Rates for House# 1: Scenario 1:

PLC Module 1		PLC Module 2		Wi-Fi	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
53.2	22.8	51.2	33.3	59.2	60.4
38.1	15.3	53.3	33.5	59.7	60.9
39.2	13.8	51.9	35.7	59.7	60.3
40	13.5	53.8	35.8	59	60

Average download Speed efficiency: 57% (Mod 1), 70% (Mod 2), 79.2% (Wi-Fi)

ii. Scenario 2: 502 AV/308 AV Adapter at socket 1, which has a heavy load connected on it, namely the IPTV, Speakers, and router. The 540 Switch/W310 AV extender is connected on Socket 6, which just has lighting and plugging load. The two modules at a distance of 50 ft. from each other.

Table 3 Data Rates for House# 1: Scenario 2:

PLC Module 1		PLC Module 2		Wi-Fi	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
12.5	4.3	17.2	6.8	60.3	24.8
10.8	4.2	16.3	9.6	56.1	23.1
12.2	4.5	15.5	7.8	56.1	25
12.6	3.6	16	8.3	37.2	7.5

Average download Speed efficiency: 16% (Mod 1), 21.6% (Mod 2), 69.9% (Wi-Fi)

iii. Scenario 3: 502 AV/308 AV Adapter at socket 1, which has a heavy load connected on it, namely the IPTV, Speakers, and router. The 540 Switch/W310 AV extender is connected on Socket ‘a’ in the basement, which has a dedicated supply and no load at all.

Table 4 Data Rates for House# 1: Scenario 3:

PLC Module 1		PLC Module 2		Wi-Fi	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
57.1	7.1	57.9	7.6	59.9	6.7
57.2	6.3	59.4	9.3	60.6	6.1
56.2	6.4	55.3	8.4	13.7	5
55.9	6.8	54.9	15.4	13	4.8

Average download Speed efficiency: 75.4% (Mod 1), 75.8% (Mod 2), 49% (Wi-Fi)

iv. Scenario 1: 502 AV/308 AV Adapter at socket 1, which has a heavy load connected on it, namely the IPTV, Speakers, and router. The 540 Switch/W310 AV extender is connected on Socket ‘c’, from the old wiring, in the basement, which just has lighting and plugging load.

Table 5 Data Rates for House# 1: Scenario 4:

PLC Module 1		PLC Module 2	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
13.7	5.9	17.3	7.3
13.8	5.9	18.7	6.9
12.9	5.1	19.1	8.1
13.3	5.7	17.8	7.3

Average download Speed efficiency: 17.9% (Mod 1), 24.3% (Mod 2)

3.1.1 House#2:

This house is relatively new, built around 2008, with the wiring system following the code of year 2007-2011. The wiring is all copper based. In this type of wiring system, there is a mixed variety of dedicated and shared sockets. The figure below shows a part of the wiring blueprint of the house. The map shows one room on the main floor and three on the second. The electrical panel, located in the garage of the house, allows 120~208 V AC voltage. The household uses Internet plan by Shaw Communications with theoretical promise of giving a data rate of 150 Mbps. The test was conducted at night, between 20:00 – 23:50 hr.

The blueprint has been designed in the software named, Microsoft Visio professional.

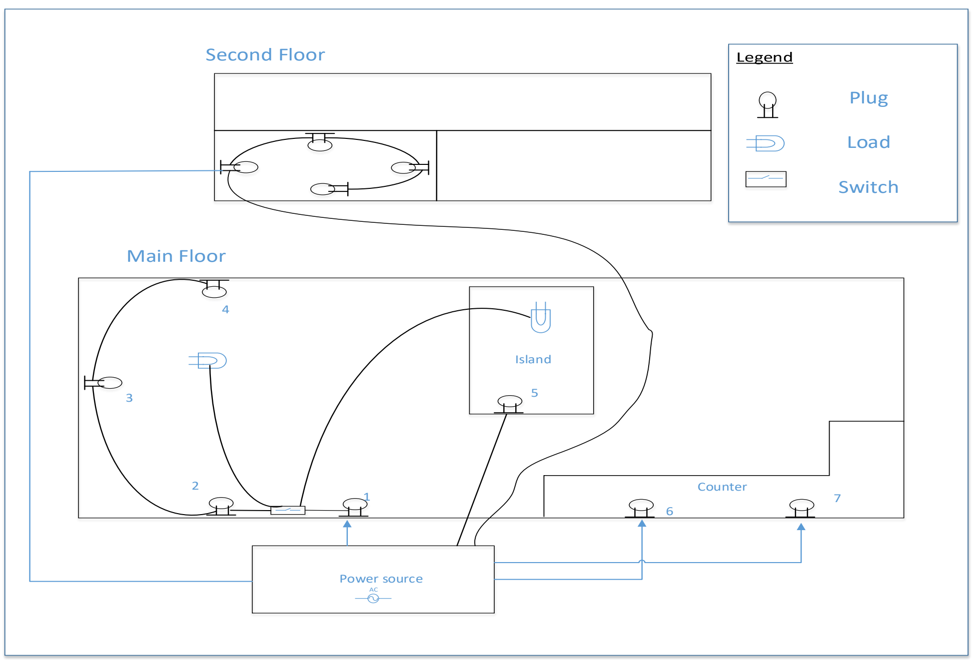


Figure 4 Wiring Blueprint - House# 2

Please note that Socket 1 and 2 are in-line on the same wall with a distance of ~ 2 ft. between them. Socket 1, 2, 3, and 4 are interconnected and support the lighting/other load. Socket 5, 6, & 7 get dedicated supply with no load sharing with other equipments. We categorize the test according to the different scenarios with both modules tested at different times, but combined here for the sake of simplicity.

i. Scenario 1: 502 AV/308 AV Adapter at socket 1, which has a heavy load connected on it, namely the IPTV, Speakers, and router. The 540 Switch/W310 AV extender is connected on Socket 5, which has a dedicated supply, with no load at all. We connect our laptop via Ethernet Cable to the switch / wirelessly (for module 2) to measure the speed, using the speed test feature available on SHAW Communications' website.

Table 6 Data Rates for House# 2: Scenario 1

PLC Module 1		PLC Module 2		Wi-Fi	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
7.18	2.27	7.78	5.18	100	15.8
7.70	2.52	6.10	6.01	94.4	14.6
8.87	2.86	10.3	5.18	77.9	14.6
6.83	2.30	6.79	4.40	72.0	14.6

Average download Speed efficiency: 5.04% (Mod 1), 5.16% (Mod 2), 60% (Wi-Fi)

ii. Scenario 2: 502 AV/308 AV Adapter at socket 1, which has a heavy load connected on it, namely the IPTV, Speakers, and router. The 540 Switch/W310 AV extender is connected on Socket 2, which just has the lighting load. Our equipments are now on the same circuit but different sockets.

Table 7 Data Rates for House# 2: Scenario 2

PLC Module 1		PLC Module 2	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
19.5	10	19.2	7.7
20.1	9.78	5.99	6.97
21.9	14.3	15.2	3.9
21.8	13.2	22.0	6.0

Average download Speed efficiency: 14% (Mod 1), 10.40% (Mod 2)

iii. Scenario 3: 502 AV/308 AV Adapter and The 540 Switch/W310 AV extender are both connected on Socket 2, which just has the lighting load. Our equipments are now on the same circuit and same sockets.

Table 8 Data Rates for House# 2: Scenario 3

PLC Module 1		PLC Module 2	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
77.6	13.2	87	15.4
82.1	13.1	91.4	15.3
81.9	14.7	83.5	15.3
77.3	15.6	76.5	15

Average download Speed efficiency: 54% (Mod 1), 56% (Mod 2)

iv. Scenario 4: 502 AV/308 AV Adapter is at socket 2 and the 540 Switch/W310 AV extender is connected on Socket 4, both of them just have the lighting load. Our equipments are on the same circuit but different sockets.

Table 9 Data Rates for House# 2: Scenario 4

PLC Module 1		PLC Module 2	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
77.2	15.8	74.7	13.9
74.2	15.6	71.3	15
62.4	14.5	88.4	13.1
73.9	15.7	71.3	14.8

Average download Speed efficiency: 48% (Mod 1), 50% (Mod 2)

v. Scenario 5: 502 AV/308 AV Adapter is at socket 6 and 540 Switch/W310 AV extender is connected on Socket 5, both of them being the dedicated circuits, with no load at all. Our equipments are now on different circuits, with the wires, of almost same length, running parallel to the main panel.

Table 10 Data Rates for House# 2: Scenario 5

PLC Module 1		PLC Module 2	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
81.3	14.8	87.2	15.3
82	14.8	88	15.5
84.5	14.1	73.5	15.1
74.6	14.2	70.1	15.1

Average download Speed efficiency: 54% (Mod 1), 53% (Mod 2)

vi. Scenario 6: 502 AV/308 AV Adapter is at socket 7 and 540 Switch/W310 AV extender is connected on second floor, with no load, except for the plugging load, on each socket. Our equipments are now on the different circuits. Socket 7 is almost at a height of 20 ft. form the panel and the second one at ~35 ft.

Table 11 Data Rates for House# 2: Scenario 6

PLC Module 1		PLC Module 2	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
37.5	14.3	18.9	12.2
42.6	14.5	32.1	7.8
41.4	14.1	25.4	8.4
39.2	14.1	24.2	10.0

Average download Speed efficiency: 27% (Mod 1), 17% (Mod 2)

vii. Scenario 7: 502 AV/308 AV Adapter is at socket 2, which just has the lighting load and the 540 Switch/W310 AV extender is connected on second floor.

Table 12 Data Rates for House# 2: Scenario 7

PLC Module 1		PLC Module 2	
Download speed (Mbps)	Upload speed (Mbps)	Download speed (Mbps)	Upload speed (Mbps)
22.8	6.0	6.4	1.1
14.1	6.1	7.6	1.1
15.2	7.4	7.1	1.2
17.2	7.5	7.6	1.2

Average download Speed efficiency: 12% (Mod 1), 5% (Mod 2)

3.2. Transformer Testing

In order for the PLC to propagate on a larger scale, over a wider network, we test the distribution transformer for its performance and reaction to the high frequency data signals. The setup was done in the Data Networks and Communications laboratory in BCIT. We use two transformers for our purpose.

In order to generate the signal, we use RIGOL DG 1032Z function/arbitrary waveform Signal generator. The specifications (obtained from the manual) of the device are given below:

- No. of Channels available – 2
- Maximum Frequency – 30 MHz
- Modulation functions available – AM, FM, PM, ASK, PSK, FSK and PWM
- Waveform used – Sine function
- Voltage Measured – Root Mean Square

We view the input/output waveforms and other parameters on RIGOL DS2072 Digital Oscilloscope. Some features (obtained from the manual) of the oscilloscope are listed below:

- LCD screen display and a number of keys to measure various parameters

- Run/Stop Key to set the state of the oscilloscope to Run/Stop mode
- Provision to connect a storage device into the USB port and you can capture a screenshot and save it to your storage device. You can save a file
- Knobs to adjust the vertical and horizontal display settings of the waveforms
- No. of channels available - 2
- 70 MHz analog bandwidth
- Auto setting of waveform display (AUTO button): The oscilloscope automatically adjusts the vertical scale, horizontal time base and trigger mode according to the input signal to realize optimum waveform display
- Built-in FFT function
- Multiple waveform math operation functions
- Embedded help in the device
- Supports multiple languages

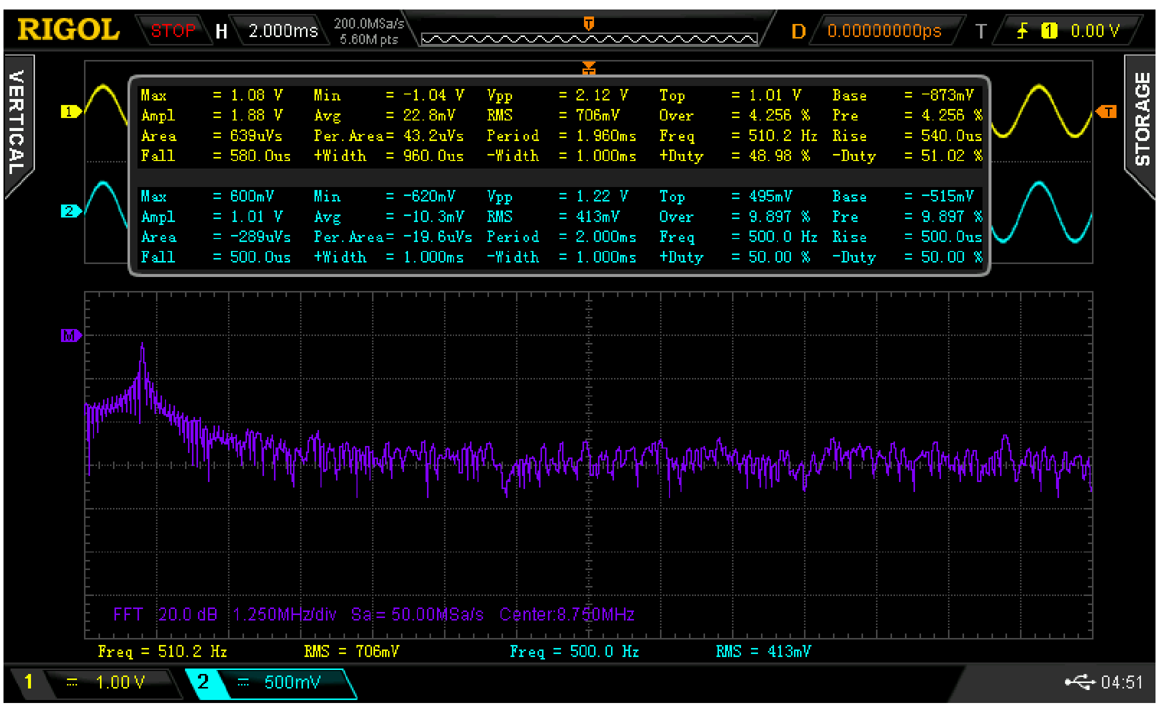


Figure 5 Oscilloscope Screen Capture for one of the frequencies in the experiment

3.2.1. Transformer 1

Initially, we use Hammond 171B transformer to test the system. It is an isolation transformer providing complete circuit isolation. Its specifications are:

- Primary 115VAC, 60Hz, Secondary 115VAC
- Electrostatic shield between primary & secondary to greatly attenuate surges & noise
- Circuit breaker in primary
- Standard 3-wire, grounded socket & receptacle

Shown below is a block diagram of the setup:

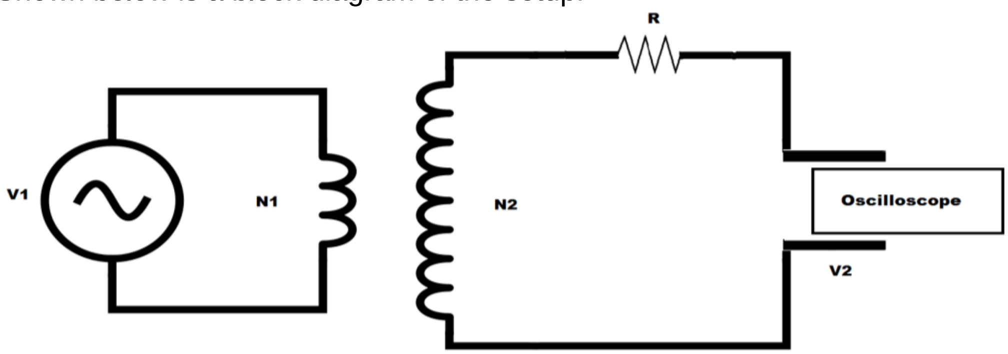


Figure 6 Block Diagram of the setup

The general setup made in the lab is shown below:

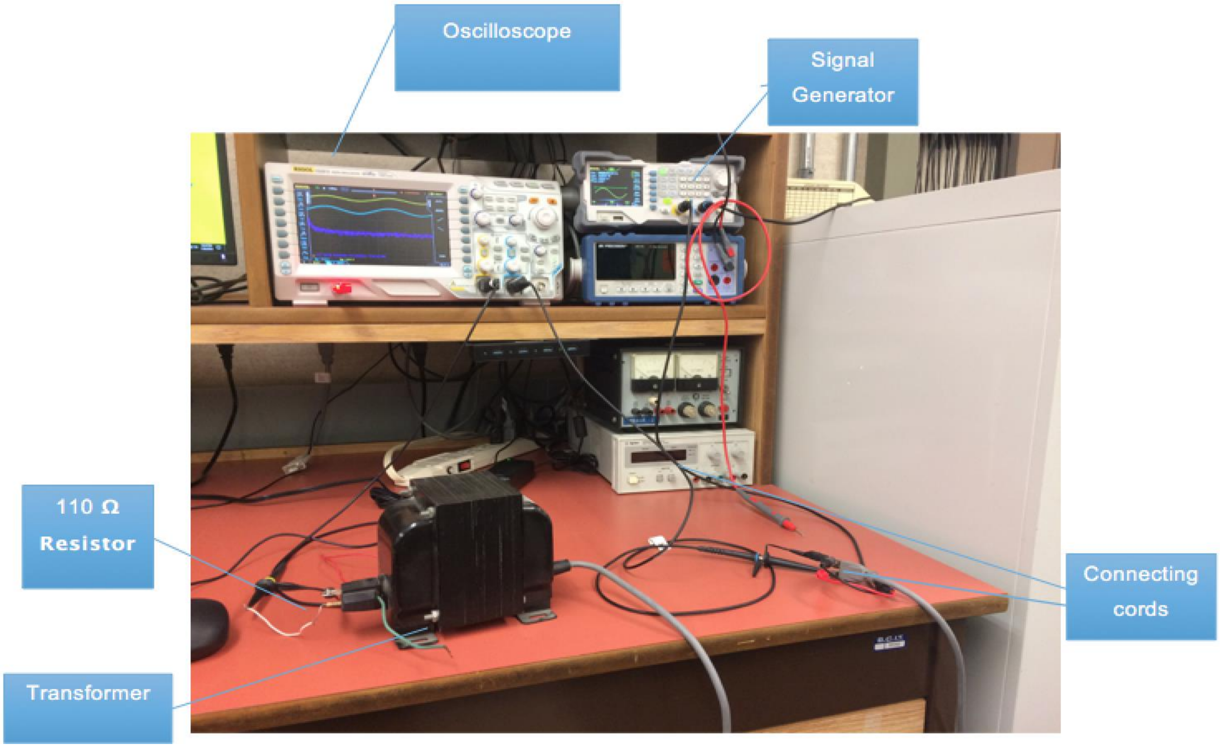


Figure 7 HAMMOND 171B Setup

The primary winding of the transformer is connected to the signal generator and the secondary to the oscilloscope with a 110 Ω resistor in between. We analyse and record the frequencies that are able to pass through the transformer. Frequency Range of 3 Hz to 1 MHz is tested.

The Root Mean Square (RMS) values of input and output voltage at different frequencies are recorded and attenuation is calculated as:

Attenuation = 20 log V2/V1 ; where V2 is the output voltage and V1 is the input voltage.

Finally, a graph of attenuation vs. frequency is plotted, with logarithmic value of frequency on the x-axis and attenuation on the y-axis.

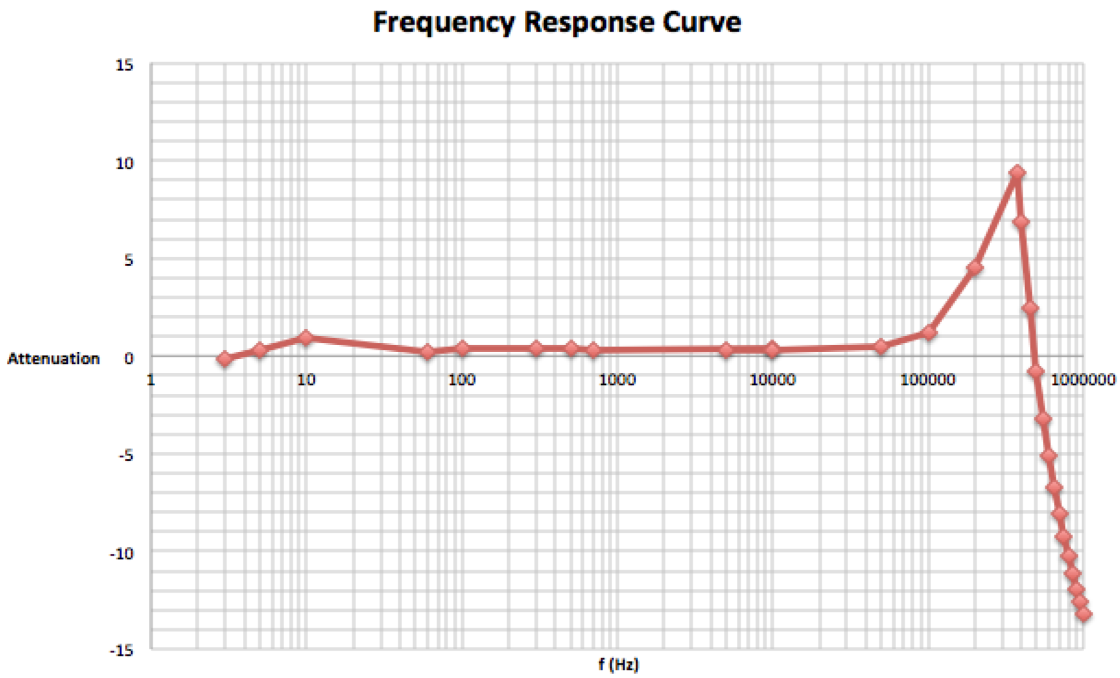


Figure 8 Frequency Response Curve for Transformer 1

3.2.2. Transformer 2

Next, we use the transformer manufactured by British Columbia Transformer Co. Ltd. provided by the BCIT electrical laboratory for the experimentation. The remaining setup remains the same as the one explained above. The specifications of the transformer are given below:

- KVA, 208 HV and 120 LV
- 1 Phase, 60 Hz
- Dry type transformer

The general setup assembled in the lab is shown below:

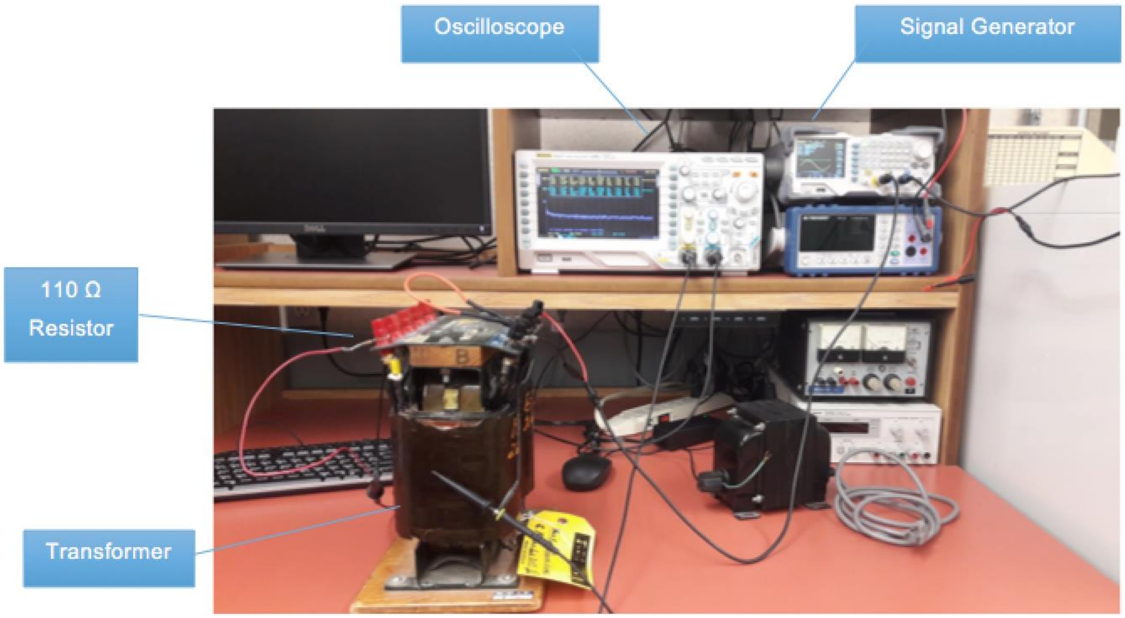


Figure 9 BCIT Transformer Setup

The input is first supplied on primary side of the transformer, that is, on X1 and X4 and the output is derived from the Secondary side, that is, the connections are made on H1 and H5 for output, which is, getting the transformer in step-up mode. In the second round of experimentation with this module, the input and output is given/ derived on the reverse sides, that is, step down transformer configuration. The graphical results of both the scenarios are discussed ahead.

1. Initial Side (Step up mode): We analyse and record the frequencies that are able to pass through the transformer. Frequency Range of 3 Hz to 1 MHz is tested.

The values of input and output voltage at different frequencies are recorded and attenuation is calculated as:

Attenuation = 20 log V2/V1 ; where V2 is the output voltage and V1 is the input voltage.

Finally a graph of attenuation vs frequency is plotted, with logarithmic value of frequency on the x-axis and attenuation on the y-axis.

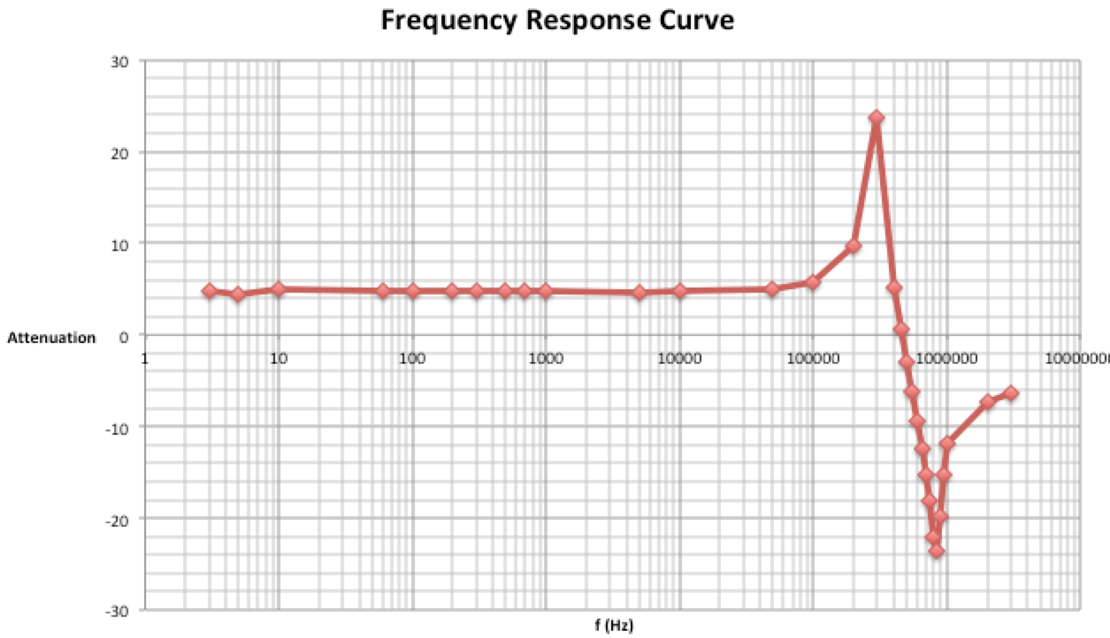


Figure 10 Frequency Response graph for Transformer 2 - Step Up

We also plot the phase difference vs. frequency plot for the transformer. For calculation of phase, we use the formula:

$$\text{Phase} = [\text{Delay}/\text{Period of Source}] \times 360^\circ$$

The digital oscilloscope shows all the readings we desire to record, including the phase difference.

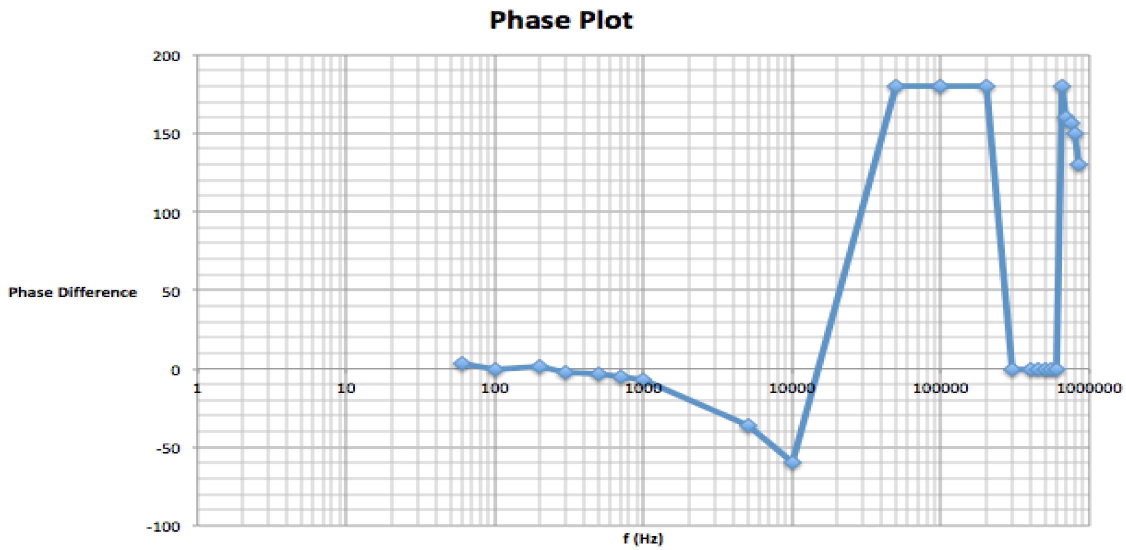


Figure 11 Phase plot for Transformer 2 - Step Up

2. Inverted Side (Step down mode): In this case, the input is supplied on the opposite side of the transformer, with the configuration opposite to the one done in the section above, that is input is at H1 and H5, and output is recorded at X1 and X4. A graph of attenuation vs. frequency is plotted, with logarithmic value of frequency on the x-axis and attenuation on the y-axis.

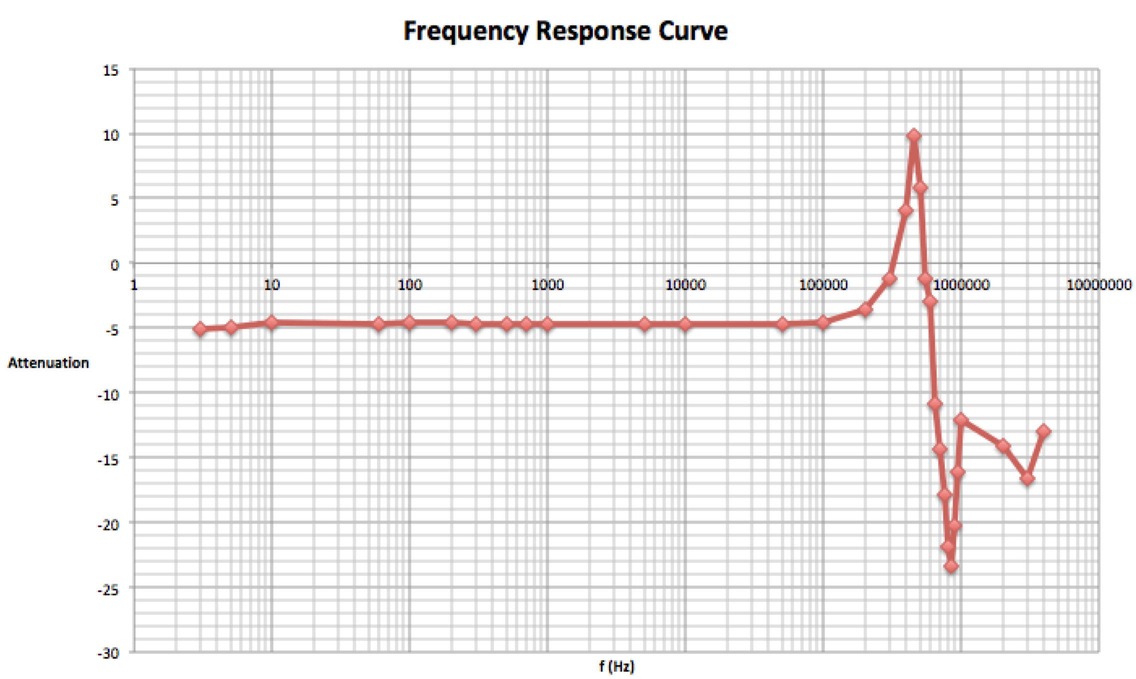


Figure 12 Frequency Response for Transformer 2 - Step Down

We also plot the phase difference vs. frequency plot for the transformer. For calculation of phase, we use the formula:

$$\text{Phase} = [\text{Delay/Period of Source}] \times 360°$$

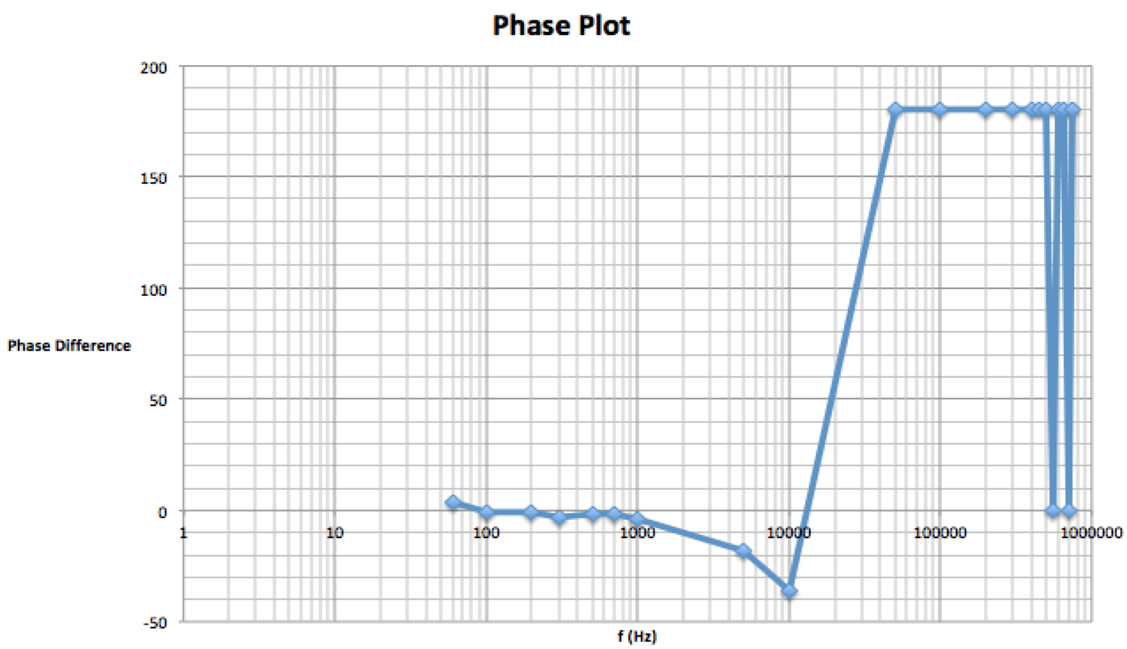


Figure 13 Phase plot for Transformer 2 - Step Down

Chapter 4.

Discussion

4.1. In home PLC

The easy plug and play installation of the modules makes it very convenient to use both the modules. A general observation in the whole process has been that the amount of load affects the performance of PLC. Also, in the house that has its wiring design according to the old code, does not show very consistent results. The module did not work in all the sockets in the household, which is due to the fact that electricity travels through different circuit breakers and hence the signal level gets dropped. The dedicated connections give much higher data rates than the ones with shared load. Using the module in the presence of the devices consuming very heavy load, such as electrical furnace, electrical stove, and refrigerator etc., hampers the device performance. It definitely showed lesser speeds than the present Wireless Fidelity (Wi-Fi) connection but was not affected by turning on of the microwave at a distance, contrary to the Wi-Fi connection that would totally stop working once the device turned on. PLC module supported IPTV, giving a very good picture quality, and supported 4K HD videos as well.

For the experimentation conducted in the relatively new house, we see the effects of load and length of wiring from the main panel, hampering the performance of the system. Scenario 5 in house# 2 is analogous to Scenario 6, with both the adapter (DHP 502) and switch (DHP 540) plugged into dedicated sockets. The only difference in the two is the height of the two switches, that is, the length of the wires connecting them to the main panel. The setup in Scenario 5 has almost 50% better data rates that the one in 6. Hence, we can conclude that the attenuation increases with the length of the electrical wires. Although, the throughput may vary with time of the day and, traffic in the data network, and interference, it definitely serves as an efficient last-mile alternative. It supports at least web browsing and high quality you tube videos, with enough speeds for daily Internet surfing.

The wireless module shows comparable performance to the wired module. However, the parametrical effects are almost same on the modules. The two modules are not interoperable.

4.2. Transformer Testing

With the testing done on the two transformers, we note that not all frequencies pass through the transformer. For the first transformer, the frequency response graph is linear up to 100 kHz frequencies, and then there is a sharp attenuation with the peak at 380 kHz, and decreasing gradually thereafter.

For the second transformer, the frequency response is similar, the graph being linear up to 100 kHz and then it suffers high attenuation with the peak at 300 kHz. On inverting the same transformer, the frequency response is similar, with no attenuation up to 200 kHz and then high attenuation with a peak at 450 kHz. Broadband signals travelling through high voltage lines would require repeaters after a certain distance and the kind of cables that carry the signal would be of better quality and would have different specifications than the regular ones.

The signals experience being out of phase at certain frequencies, as can be observed from the graph. The oscilloscope does not show a consistent phase reading at frequencies above 200 kHz, that is, it keeps fluctuating between 0°, 90°, & 360°. No value is shown between 750 kHz and 890 kHz.

Chapter 5.

Conclusion and Future Work

Power Line Communication is a vast area of research and it is a technology that many industrial sectors look up to. It has advanced by many levels in the past few decades and is continuing to do so. Many challenges have been addressed by the research community on the use of a channel not initially designed for data communication.

This project included the study of types of Power Line Communication networks and the standards and specifications established for them. We tested the PLC HomePlug module manufactured by D-Link® in a LV setup. Different scenarios were setup and parameters recorded. We saw the effects of load and distance from the main panel, on the device performance. The results were discussed in detail in the section above. For the testing on the transformer, we found that many frequencies do not go through the transformer and showed high attenuation at certain frequencies. No testing was done on a live transformer since performing a test on an energised transformer needed special safety training and due to paucity of time, it was not possible.

The future work of this project would include experimentation on an energised transformer for different frequencies. It would be worthy to notice the changes for the same transformers on being energised. Secondly, more tests can be performed on the LV network with advanced in-home PLC modules, one of them could be the module using HomePlug AV2 specifications. Interoperability with different wireless technologies still remains an area of research.

With the advancement in channel modelling and standardization, Power Line communication has a possibility of penetrating into every sector in the field of communication. An increased demand of PLC is expected in Smart Grid applications.

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