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PROTOTYPE OF COUPLING UNIT NETWORK FOR POWER LINE COMMUNICATIONS

by

BHARATH SRINIVASAN
B.E. University of Madras, 2003

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the School of Electrical Engineering and Computer Science
in the College of Engineering and Computer Science
at the University of Central Florida
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2006

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ABSTRACT

Power Line Communications has made impressive strides since its introduction. Power Line Communications (PLC) or Broadband over Power Lines (BPL) is the method of transmitting broadband signals over the power lines and making it available at the power outlet in homes. It provides last mile communication and makes use of existing power lines to transmit signals, thereby eliminating the need to lay cables all over again. PLC is fast becoming a commercial reality in the United States. The Federal Communications Commission (FCC) is working toward making PLC a standard with particular emphasis on power emission issues and interference with nearby bands. Power companies, vendors and ISPs (Internet Service Providers) have tied up to bring this new technology to market.

The Power line environment is inherently unpredictable due to interference, low signaling impedance and the highly linear operating environment that PLC transmitters require. The coupling unit in the PLC system acts as a filter and eliminates the harmful AC signal from interfering with the broadband signals. A coupling unit amplifier topology that provides gain equalization and wideband mitigation to the effects of low-impedance loads on PLC in the high frequency range has been explored in detail in this study. The amplifier is verified for its performance by means of circuit simulation using industry-standard software such as Agilent's Advanced Design System (ADS). The coupling unit has also fabricated to verify the performance. An experimental setup for verifying the performance of the coupling unit using a PLC transmitter and PLC receiver has also been proposed.

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LIST OF ACRONYMS/ABBREVIATIONS

ADS	Advanced Design System
BPL	Broadband over Power Line
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
DSSS	Direct Sequence Spread Spectrum
GSM	Global System for Mobile Communications
OFDM	Orthogonal Frequency Division Multiplexing
FCC	Federal Communications Commission
HF	High Frequency
IEEE	Institute of Electrical and Electronics Engineers
ISP	Internet Service Provider
NTIA	National Telecommunications and Information Administration
PLC	Power Line Communications
RF	Radio Frequency
UMTS	Universal Mobile Telecommunication System
UWB	Ultra-Wideband

CHAPTER ONE: INTRODUCTION

1.1 Overview

Due to the rising need to provide ubiquitous internet connectivity, technologies have been developed to provide secure information at nominal costs to previously inaccessible places. The latest to hit the tech world goes by the name “Power Line Communications”. Also called Broadband over Power Lines (BPL), PLC or Power Line Communications transmit data and voice signals over the existing power lines, thereby eliminating the need to lay cables all over again and ensuring last-mile connectivity.

Cellular and Wire line Communication have made rapid progress over the past decade. Code Division Multiple Access was developed using DSSS (Direct Sequence Spread Spectrum) Technology. Originally used by the military, DSSS ensured that signals were not intercepted by enemy camps. The idea was rather simple; to spread the data over a wider bandwidth than would be actually necessary to send it and thereby rendering the signal to be less susceptible to narrow band interference. When the same concept was adopted by Qualcomm co-founders; Dr. Andrew J. Viterbi and Dr. Irwin Jacobs, it was also found that such signals also posed resistance to noise in multi-path environments. Thus, CDMA (Code Division Multiple Access) was born and provided a viable alternative to the existing GSM (Global System for Mobile Communications) standard. The CDMA standard has progressed rapidly from its inception and now has many variants, such as the CDMA 2000, CDMA 2000 1X-EVDO, CDMA 1X-EVDV and more

recently, W-CDMA or what is otherwise known as Universal Mobile Telecommunication system (UMTS).

Orthogonal Frequency Division Multiplexing (OFDM) is another technology that has been in literature for quite a long time now. UWB (Ultra Wideband) was developed on the basis of OFDM and has had tremendous success in in-door environments. UWB transmits billions of pulses across a wide spectrum of frequencies and the receiver translates the pulses into data by listening in for a familiar pulse sequence sent by the transmitter. Modern UWB systems occupy extremely wide bandwidths and the combination of using multiple bands and OFDM modulation provide significant advantages over other methods of communication. UWB uses a broader spectrum and that, combined with low power improves speed and reduces interference with other wireless spectra.

BPL service providers use OFDM to encode the data by splitting the RF signal into smaller sub-signals that are then transmitted at different frequencies, thereby increasing speed and reliability. PLC has many advantages over other technologies that will be discussed later in this chapter. However, one major drawback that is worth mentioning right here is that PLC causes interference in the high frequency band. Amateur radio operators complain that PLC has polluted the radio spectrum causing a rise in the noise floor in urban areas.

Originally introduced in Europe, PLC has gained prominence in the United States. The Federal Communications Commission (FCC) has had the unenviable task of bringing this technology to the forefront and they have placed considerable emphasis on power transmission issues. Several vendors and wireless networking companies have tied up with power companies to deploy the standard. Currently, Ambient Corporation, Amperion, PPL Utilities, Southern

Telecom and Progress Energy are some service providers deploying BPL networks at various locations across the United States.

The thesis begins with a brief introduction to Power Line Communications. The advantage of using PLC is that the infrastructure is already present and can be used to provide communication to remote places that would otherwise be difficult to undertake under normal circumstances. In-house BPL and Access BPL are two forms of BPL that are discussed from a technology stand-point. This is followed by some key advantages and disadvantages of using PLC as a communications technology.

The second chapter goes over the system components of PLC, PLC system architecture, interference issues surrounding PLC and FCC regulations on the same. This is followed by a thorough literature review on key areas that relate to the nature of this thesis. The topics studied include noise analysis on the power line environment, design of impedance matching networks for PLC transmitters and coupling unit topologies that work in the high frequency range.

Power Line Communication requires a highly linear operating environment that is quite difficult to achieve. They suffer from interference and have low input impedance. A particular coupling unit amplifier topology has been studied in detail in the third chapter. The amplifier is simulated using Agilent's ADS (Advanced Design System) and the results of the circuit simulation have been shown.

The final chapter discusses the PLC experimental setup that is to be performed on the fabricated amplifier coupling unit topology. This is followed by results, conclusion and future work that can be undertaken.

1.2 What is Power Line Communications?

As stated previously, PLC transmits broadband data over power lines and makes it available at the power outlet in homes. The idea sounds exciting but, is not novel as such. Power companies have always used AC power to transfer data but the speed of data transmission over power lines is way slower than the high speed requirements of applications such as voice, video and data. BPL systems get around this by coupling radio frequency (RF) data signals onto the existing electric power lines to provide high speed data communication.

The high frequency (1MHz – 30 MHz) data signals are transmitted through the same power lines that carry low frequency electricity signals (50 or 60 Hz) to household or business. This enables both the signals to coexist on the same wire (Wilt, 2004). In other words, BPL systems transmit RF signals over the low and medium voltage power lines in the high frequency range and enable users to access the Internet. The biggest advantage in using PLC is that the last-mile infrastructure is already present. Power lines literally run to every single home providing electricity to millions and thus, PLC avoids the hassle of laying cables all over again. In the future, household appliances could be networked.

RF energy over power lines cause interference to adjacent frequency bands. Power lines that radiate RF energy are similar to antennas emitting signals along their path as shown below.

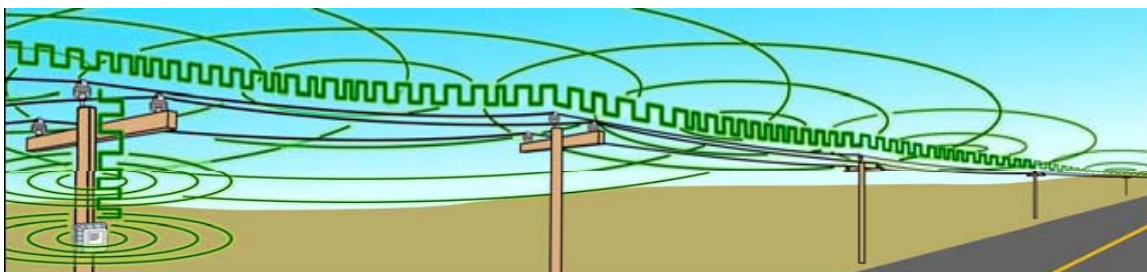


Figure 1: Power Line Network (ARRL, 2005)

1.3 In-house BPL

In-house BPL is as simple as it sounds. They are present inside of residences and are designed using the electrical wiring inside the building under the rules laid out by the HomePlug Alliance. In-house BPL is a home networking technology that uses the transmission standards developed by the HomePlug Alliance. Products for in-home networking using the electric outlets in your home (or office) are available in stores now. In-house BPL products can comply relatively easily with the radiated emissions limits in Part 15 of the FCC's Rules, because the products connect directly with the low voltage electric lines inside your home or office. In-house BPL has no relation to Access BPL. Experimental tests are still underway as far as In-house BPL is concerned.

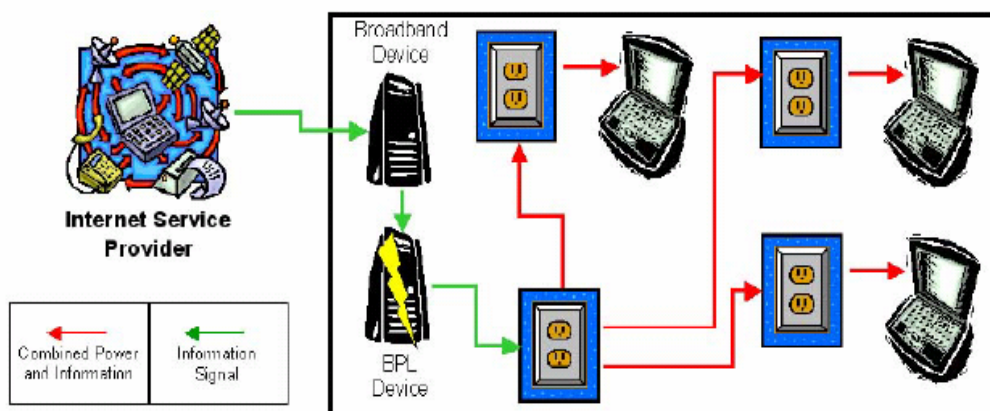


Figure 2: In-house BPL

The figure above shows the schematic of a standard In-house BPL layout. It is seen that the signal is easily sent to the houses using the power lines. The FCC defines In-house BPL as a carrier current system installed and operated on an electric utility service as an unintentional

radiator that sends radio frequency energy on frequencies between 1.705 MHz and 80 MHz over medium voltage lines or low voltage lines to provide broadband communications and is located on the supply. In-house BPL makes use of the existing broadband connection and so the cost of setting up the network infrastructure is negligible. The signal is carried throughout the house over the low voltage electrical wiring. Special cables are used to connect the NIC (Network Interface Card) to the power outlet in the house.

1.4 Access BPL

Access BPL is the second kind of BPL. The signal is carried over medium voltage power lines. Electrical distribution lines, both overhead and underground are used to provide internet access to homes and businesses. As the wiring is large, often overhead and extends across entire communities, access BPL systems pose a significant interference potential to over-the-air radio services. Amateur Radio is not the only potentially affected service from these types of systems. There are a number of different techniques used in access BPL, from spread spectrum to OFDM (multi-carrier signals). Studies done by amateurs in Europe, Japan and the US leave little doubt that access BPL that uses overhead electrical distribution wiring poses an interference risk to HF. Medium voltage power lines are the electric lines that you see at the top of electric utility poles beside the roadways in areas that do not have underground electric service. Typically, there are three phases: A, B and C each carrying several thousand volts.

FCC defines Access BPL as a carrier current system, operating as an unintentional radiator that sends radio frequency energy to provide communications on frequencies between 1.705 MHz and 80 MHz over LV electric power lines that are not owned, operated or controlled

by an electric service provider. The internet service provider runs a large bandwidth connection to a power substation. Access BPL is capable of delivering data rates in excess of 24 Mbps. The figure below depicts Access BPL pictorially.

1.5 The HomePlug Alliance

The HomePlug Alliance is an association of companies within the electric utility industry in the United States. The companies include Cogency, Panasonic, Radio Shack Corp. and Sharp. Twenty participating member companies accompany this group and some of the big players include Motorola, Philips Electronics, Sony Corp. and France Telecom. The HomePlug Alliance developed the HomePlug standard and they meet the current FCC Part 15 requirements for current carrier systems. The aim of the HomePlug standard is to provide interoperability between consumer devices by setting a MAC protocol as well as the physical signaling techniques to be used a form of orthogonal frequency division multiplexing (OFDM) modulation using up to 76 carriers in the band 4.5 MHz to 21 MHz. The throughput rate of a typical HomePlug standard is 14 Mbps with extrapolated rates going up to 20 Mbps.

1.6 Advantages and disadvantages of PLC

The biggest advantage of BPL is that the infrastructure is already in place and no change in business or household wiring is necessary to implement the BPL system. As a result, the BPL services can be rendered at a faster rate and the amount of capital expenditures required are reduced. The Federal Communications Commission (FCC) estimated that it would cost \$10.9

billion to wire all of rural America for broadband. BPL services are offered to the customers at lower prices (\$20-\$40) than DSL or cable which could influence customers who already have DSL or cable to switch to BPL (Breen, 2004).

BPL enables networking machines within a building. It provides broadband connection in every socket in every room making it possible to network all kinds of common appliances in a household. BPL offers to the residential and the business customers not only voice, video, and data services but also others such as mapping and home management abilities that work more reliably and faster than in the past (Wilt, 2004). The usage of BPL increases national security. It is said that the implementation of BPL could offer both consumers and Internet Service Providers (ISPs) a third broadband access solution (Amperion, 2004).

The biggest potential hurdle for BPL appears to be interference. Ham radio operators have claimed that BPL makes it difficult to operate their devices. Recently, however, this issue has subsided somewhat, as the FCC has endorsed BPL and is establishing testing requirements for the equipment. The problem with interference is multi-faceted and to some extent difficult to fully comprehend. For instance, a very low powered signal can propagate hundreds or thousands of miles. As such, the power lines are not designed for data transmission at high frequency and so they act as radiators. When data is transmitted at high frequencies there is a loss of signal or leakage of signal through the wires because they are not shielded. This again results in signal loss (Wilt, 2004).

BPL pollutes the radio spectrum, causing a large rise in the noise floor in urban areas akin to radio smog. The American Radio Relay League (ARRL) has demonstrated the interference effects of BPL on amateur radio communications. They also demonstrated strong interference from quite low power high frequency (HF) transmitters into the BPL network, using

BPL test sites running in the U.S. (ARRL, 2004). BPL providers argue that by tweaking their systems to not use frequencies that aren't in use locally, they can coexist as a viable means of communication. The assumption is that they won't interfere locally with anyone, but due to the propagation characteristics of HF, it could cause likely long distance interference or an increased noise floor across the HF bands. Sharing bandwidth is a problem because the available bandwidth over the wires is fixed and so, the bandwidth is split among the users. This indicates that more number of users implies less bandwidth available for users. There is a possibility of impedance mismatch which can occur when two different appliances are connected to the power supply which interacts with each other. If the devices do not have the same impedance, mismatch occurs and results in loss of signal.

Another major disadvantage is that due to the signal loss that take place in a wire, there is high attenuation and there is a need for repeaters at regular intervals. BPL is susceptible to noise and due to the propagation characteristics of HF, it is likely that long distance interference or an increased noise floor across the HF bands could occur. Such problems are hard to track down to a particular system and hundreds of these systems operating across the country could have a cumulative effect (Breen, 2004).

CHAPTER TWO: LITERATURE REVIEW

2.1 Components of a PLC system

Just as with any other communications technology, Power Line Communications need routers, switches, and repeaters to provide the network infrastructure for satisfying the bandwidth needs of users and services provided. The PLC network has to meet additional requirements as both data and electricity need to be transmitted along the power lines. This requires a number of intermediate network devices positioned at the substation (S-Node), mid-span as repeaters (R-Node), at the distribution transformer (X-Node), and in the home in the form of customer premises equipment or Gateway GW-Node (George Jee *et al.*, 2003)

The Substation or S-Node provides connectivity between the BPL network and the voice/data network. The Power Line network and the data network operate in the high frequency range at around 60 MHz. The two signals can thus coexist on the same wire without any interference issues. The Transformer X-Node transmits data from medium to low voltage lines. The RF signals are attenuated as they are transmitted along the power lines and hence repeaters are used at regular intervals to regenerate the signal. Couplers act as High Pass filters that make last mile connectivity a reality. Couplers bypass the distribution transformers and allow only frequencies in the 1-60 MHz range to pass through. The Gateway GW-Node is the last node in a PLC system and they help in providing internet and other applications at the user end. The PLC network interface is one of the most important blocks and they give the signal to the power outlet by means of an appropriate electrical plug. OFDM (Orthogonal Frequency Division

Multiplexing) is the primary method of encoding for the PLC network interface and helps provide physical and data link layer encryption.

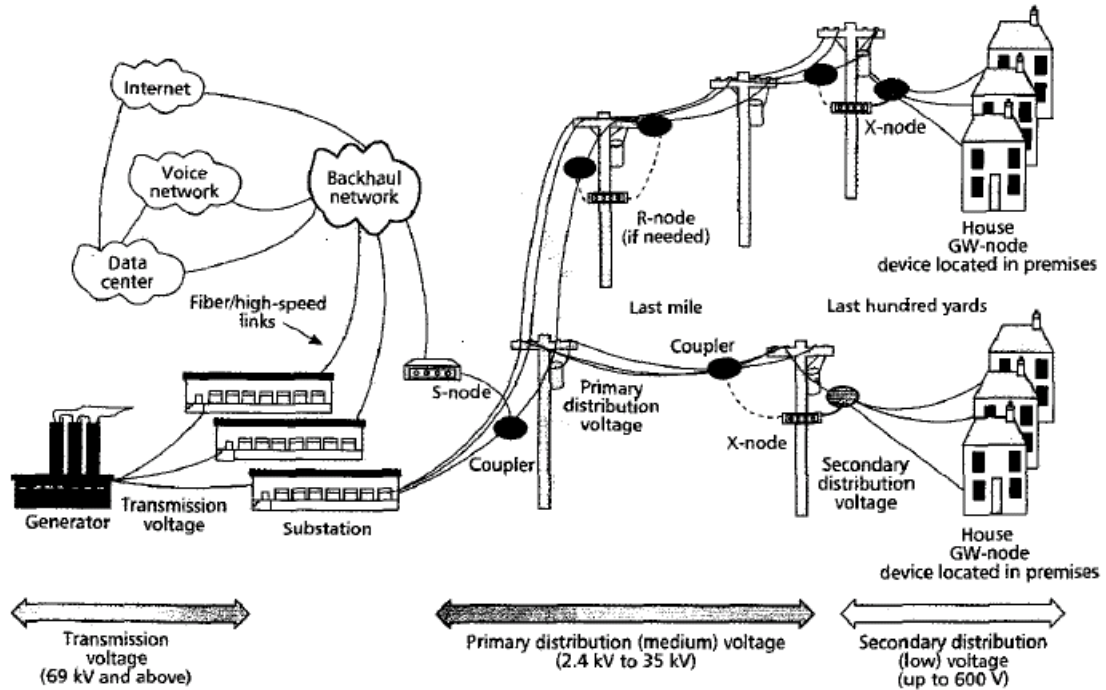


Figure 3: General PLC System Architecture

The above figure gives a clear picture of the system architecture in a PLC communication system. It clearly shows that the existing methods of transmitting signals such as fiber optic cables, power lines are used to carry the signal from the internet backbone to the user end.

2.2 Power Line Communications System Architecture

The National Telecommunications and Information Administration (NTIA) identified three architectures for Power Line Communications (NTIA Report, April 2004).

2.2.1 System # 1

OFDM spreads the data signal over a larger bandwidth than is normally required to send the signal. This data signal goes into the injector where it gets converted into the OFDM format. The coupler that is present at the injector couples the signal onto one phase of the medium voltage line. The coupler that is present at the injector also converts the BPL signals into a format that can be used at the internet backbone. BPL extractors make this two-way data communication possible. The users access this BPL signal at homes using in-house BPL devices.

The frequency bands used by the injectors and extractors on the medium voltage power lines and those used by the customers at the other end are not the same. The two frequency bands are F1 and F2 respectively. Carrier Sense Multiple Access (CSMA) in combination with Collision Avoidance (CA) is used to regulate data traffic and optimize contention for the channel. The system is also designed to accept some amount of co-channel interference.

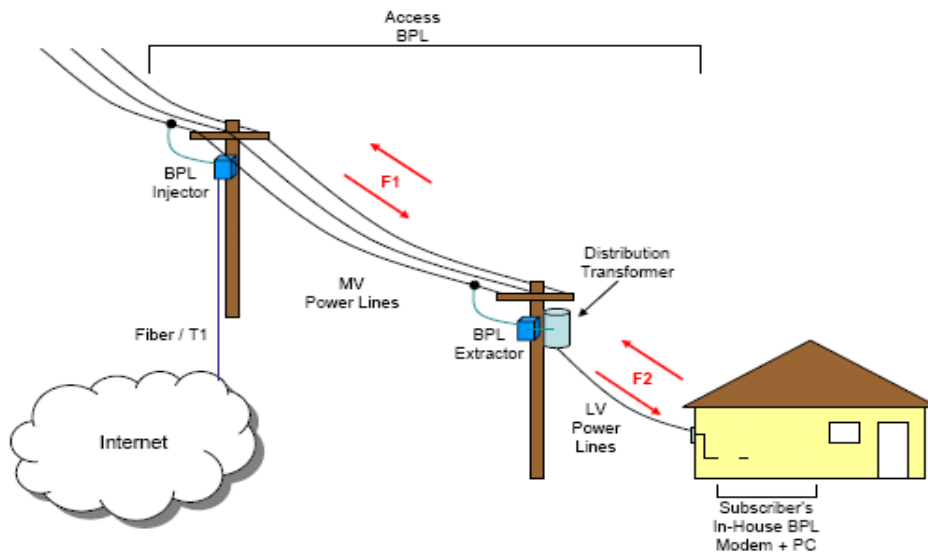


Figure 4:PLC System 1 Architecture

2.2.2 System # 2

There is one major difference between System 1 and System 2 in the manner in which the data signal is delivered to the users. While System 1 use injectors and extractors and deliver it to the subscribers, they do not however convert into another signal format. After extracting the signal from the medium voltage lines, the signal is converted into an IEEE 802.11b WiFi signal and then sent to the subscribers through an interface (modem). IEEE 802.11b WiFi signal is just one method of transmitting and other kinds of signals can also be experimented with.

As with System 1, System 2 also employs mechanisms to separate the BPL signals traversing along the power line. The frequency bands used for upstream and downstream traffic are different from each other. This again helps in minimizing co-channel interference with other nearby BPL devices. Repeaters are used at regular intervals to regenerate the signal. BPL repeaters transmit and receive signals on different frequencies and also use frequencies different from those of the injectors and extractors. Repeaters however decrease the overall bandwidth of the BPL system and thus, additional frequency bands cause delay and latency of the data signal.

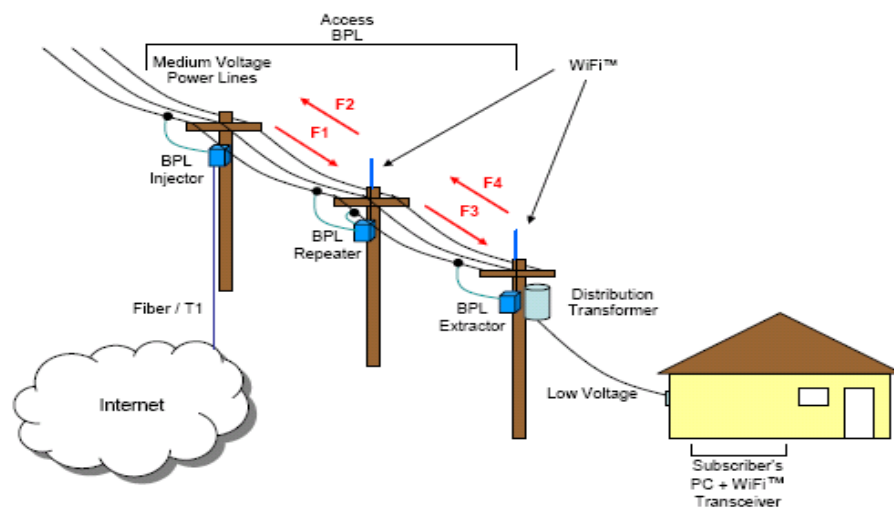


Figure 5:PLC System 2 Architecture

2.2.3 System # 3

System 3 differs from System 1 and System 2 in that it used Direct Sequence Spread Spectrum (DSSS) instead of OFDM to transmit the data over the power lines. Again, CSMA is used to minimize channel contention in the same frequency band and System 3 also tolerant toward co-channel interference between adjacent cells. The mechanism by which the data signals are transmitted from the internet backbone to the subscribers is different in BPL systems. The injector provides the interface to the Internet backbone (T1 or fiber link). As is customary with all the three systems, a large number of repeaters are mounted to regenerate the signal losses on the power line. Repeaters give the best communication path between the repeaters and the power line but they also decrease the overall bandwidth. They also use up other frequency bands in the process and also introduce latency and delay in the data signal. The signal is coupled onto the power line using a pair of couplers on a phase and neutral line.

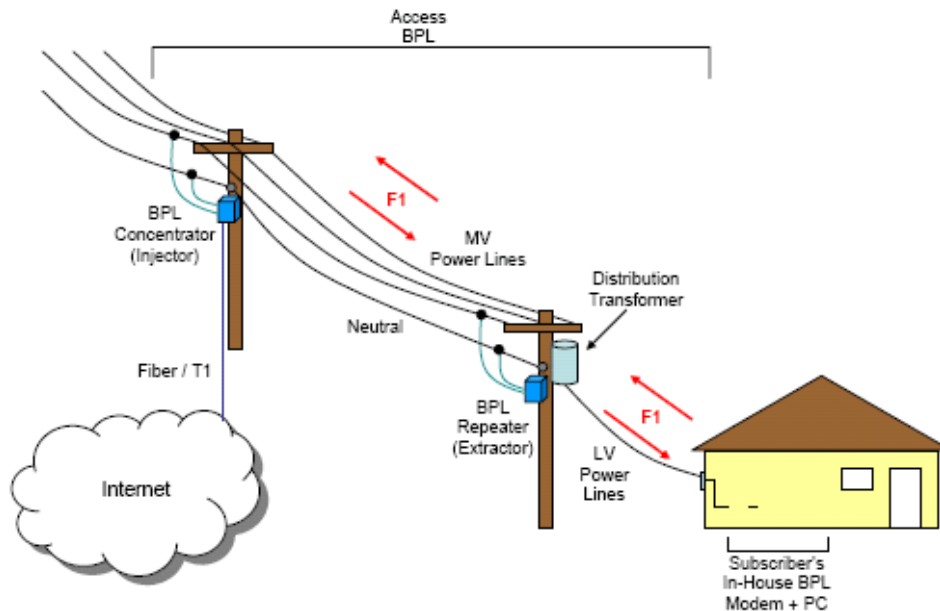


Figure 6:PLC System 3 Architecture

2.3 Interference Issues

BPL systems are known to interfere with adjacent frequency bands. The existing Part 15 compliance procedures tend to underestimate the peak field strength and thus interference is often a neglected issue. Thus, interference tends to be much more than expected. The National Telecommunications and Information Administration specify several means by which interference caused by Power Line Communications to be prevented or eliminated. NTIA suggested that specifying some mandatory parameters on BPL systems would enable operators to bring down interference levels. NTIA also recommended that BPL developers should consider several interference prevention and mitigation procedures. Some suggestions included use of minimum output power, avoiding locally used radio frequencies, differential-mode signal injection oriented to minimize radiation, using filters and terminations to extinguish BPL signals on power lines that were not needed and judicious choice of BPL signal frequencies to decrease radiation. Vendors and providers are already taking such steps in that direction. This is a dicey situation where increasing signal will induce noise (interference) in other frequency bands and cannot be done away with easily. The only way to get around this is to decrease signal to the absolute minimum level to get transport across the wire. Typically, the signal level is far lower than the medium voltage noise already emanating from many lines. So, the idea is to minimize emissions and use a very wide OFDM signal to spread energy across a band. Essentially, OFDM divides any given frequency into subcarriers that are separated at the receiver without interference. OFDM technology enables operators to comply with the requirement that frequencies liable to interfere with existing customers be notched out and also makes using

smaller amounts of power realistic, as signals spread over a wider band will not have to compete with each other.

2.4 FCC Regulation

Broadband power line communications systems are treated in Part 15 as non-radio communications digital equipment. This part of the FCC Rules and Regulations describes the primary requirements for unlicensed low power radio communications devices and emissions from non-radio communications digital equipment that might otherwise cause electromagnetic interference (EMI) to radio communications services. These systems are referred to as current carrier systems and specific arrangements are in place for systems operating on frequencies in the band 9 kHz to 30 MHz. The FCC Rules and Regulations specify limits for both conducted and radiated emissions for current carrier systems. Section 15.107 sets out the conducted emission limits for all Part 15 devices connected to the AC power supply, including devices used in current carrier systems (FCC Part 15, 2004). These requirements apply to the terminal devices only. The radiated emission limits for current carrier systems are the general radiation emission limits for non-specified devices that radiate either intentionally or unintentionally. These limits are significantly higher (greater than 100 times) than limits found in the regulation of other countries for these devices at HF frequencies.

2.5 Power Distribution Circuits for Communication

The use power-distribution circuits for communication have been studied for a little over two decades now. The input signaling impedance and attenuation are the other factors that need to be considered while modeling and implementing a power line communication network (Morgan H.L. Chan et al, 1986). Morgan H L Chan et al made real-time experiments and the results and conclusions they arrived at were in keeping with these trends. Attenuation usually exceeded 20 dB except for at very small distances. Proper impedance matching networks had to be designed. The experimental setup that was used by these researchers will be discussed. It consisted of a signal generator followed by a power amplifier and the coupling network at the transmitter side. The live network performed the role of a channel, followed by a coupling network at the receiver, a resistive load and the voltmeter to read the signal.

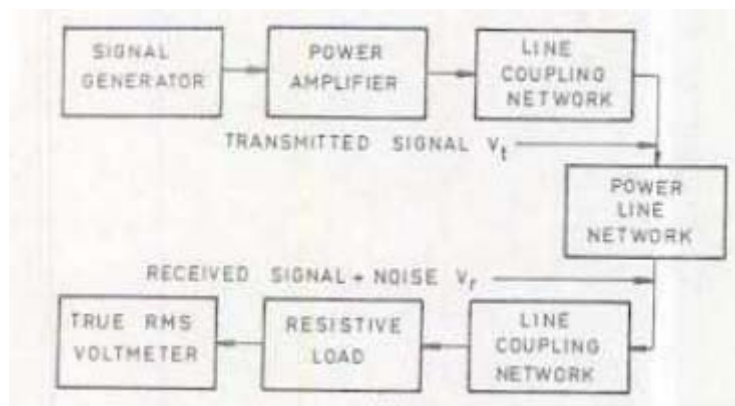


Figure 7: Experimental setup for measuring attenuation

The line coupling network consisted of a 1:1 Sprague transformer and was perhaps the single most important block in the entire setup. This coupling unit network was designed for proper impedance matching and had to make the power line signaling environment as predictable as possible. The figure below shows the coupling network.

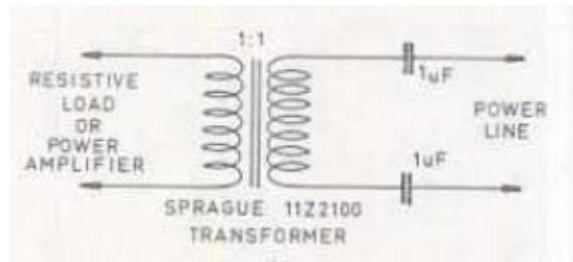


Figure 8:Line Coupling Network

Attenuation measurements were made at various locations (hospitals, residential apartment buildings, industrial buildings) at various times during the day. The attenuation levels were found to be different at different frequencies for the same building and also varied with the kind of building in question. It was also found that the attenuation increased with increase in frequency while noise was found to reduce with increasing frequency. Network loading was one of the main reasons for this anomalous behavior. Thus, the choice of signaling frequency was very important as it had to be a compromise between attenuation and noise measurements. An alternative to the above idea would be to use error control codes and other protocols to improve the signal-to-noise ratio. ARQ (Automatic Repeat Request) could be used to enhance the throughput rate that would intelligently adjust in accordance with the power line network quality. The results for attenuation vs. frequency for two buildings are as shown.

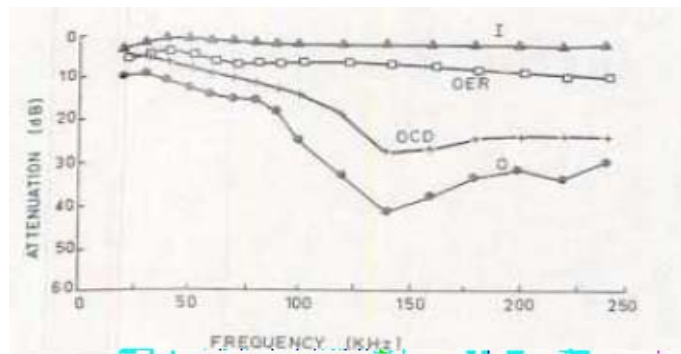


Figure 9:Attenuation versus frequency (single family home)

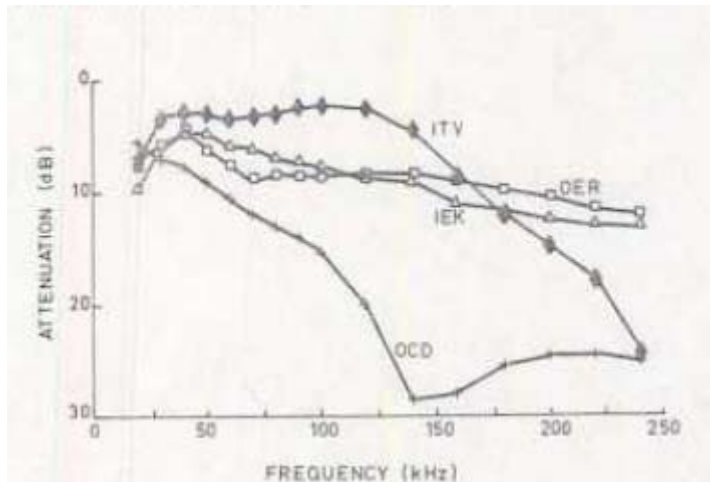


Figure 10: Attenuation versus frequency (industrial buildings)

Studies on the Electro-Magnetic noise measurements on residential power distribution circuits have been conducted over the years to get an idea. These experiments were designed to give an insight into how the different household appliances interfered with signal communication when power lines were used as the medium. Preliminary measurements at residential sites showed that the noise level depended primarily on the appliances that were currently in use at the residence and at other residences connected to the same distribution transformer.

The primary sources of noise in a residence are universal motors, light dimmers, and television receivers (Roger M. Vines et al, 1984). Noise was measured by directly measuring the steady-state conducted voltage and current produced by commonly available household devices. The current and voltage spectrum measurement setup for household devices are shown here.

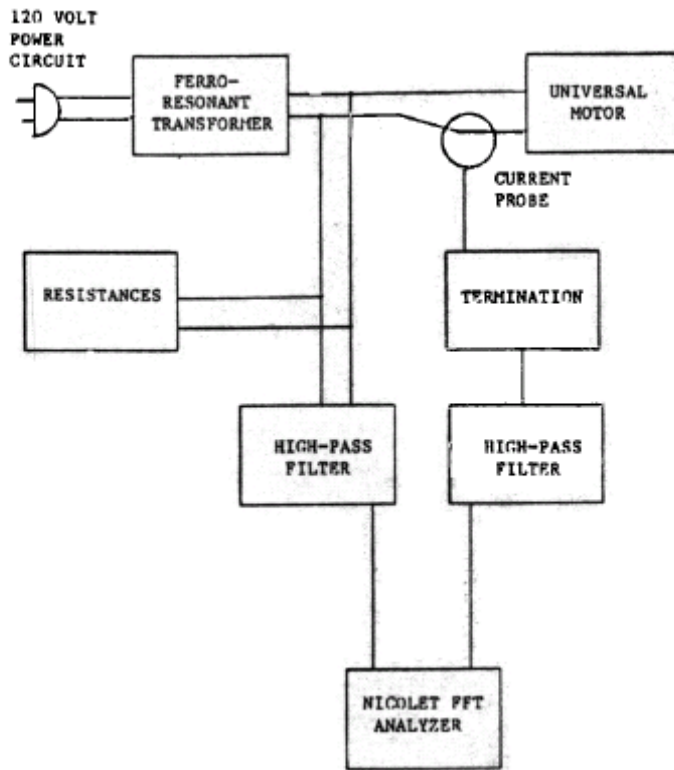


Figure 11: Current and voltage measurement setup

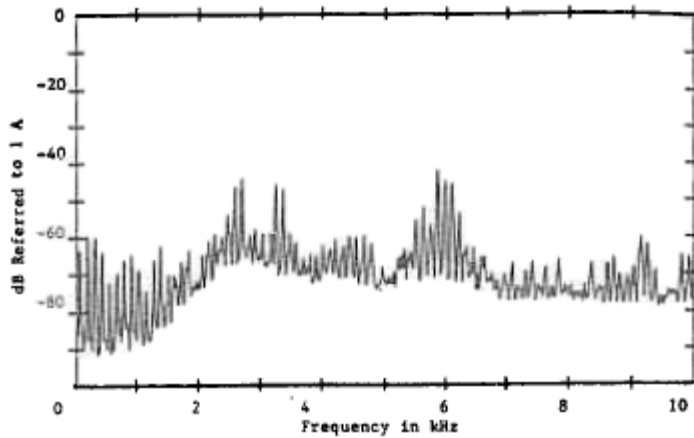


Figure 12: Current spectra for universal motor

This paper studied the effects of the above mentioned devices under experimental conditions at an office. Almost without exception (one anomalous measurement), the residential

voltage spectra measurements agreed with calculations based on measurements made under controlled conditions. It was found that, in order of decreasing strength, appliances used at the residence followed by appliances at a neighbor's residence and then the background noise from the circuit present in the primary side of the distribution transformer were the main factors.

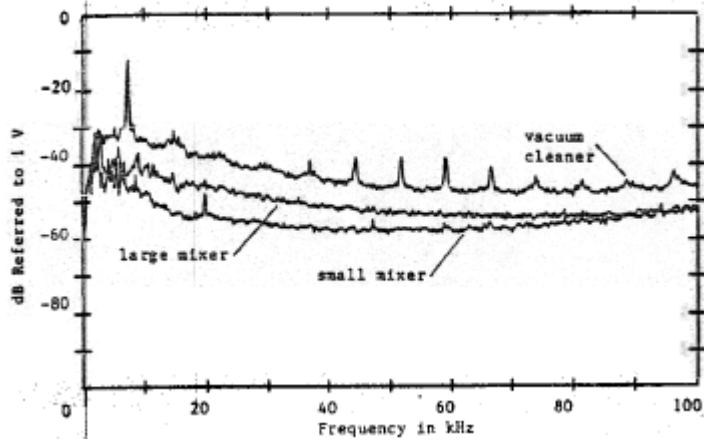


Figure 13: Voltage spectra for three appliances with 60 Hz supply

2.6 Analysis of Broadband noise in PLC environment

The third paper that will be focused here analyses noise in power line networks. An interesting aspect of a Power Line Communication network is that it is not representative of an AWGN (Additive White Gaussian Noise) but is dominated by narrow-band interference and impulsive noise in the high frequency range (Manfred Zimmermann et al, 2000). This paper researches the influence of impulsive noise on the power line environment up to 20 MHz. For the sake of analysis, different kinds of additive noise are considered, namely

- Colored background noise,
- Narrow band noise

- Periodic impulsive noise that is asynchronous to the mains frequency
- Periodic impulsive noise that is synchronous to the mains frequency
- Asynchronous impulsive noise

Colored background noise, narrowband noise, and periodic impulse noise asynchronous to the mains frequency tend to be stationary over long periods of time whereas the last two types of noise vary even over very small periods of time. The measurement setup consists of a coupling unit that is used to get hold of the signal which feeds the signal to the DSO (Digital Storage Oscilloscope) which is in turn connected to a PC.

It was found that, in the frequency range up to 5 MHz, the interference was primarily meant to be narrow-band noise. Colored noise was spotted up to 2 MHz just above white noise and between 10-15 MHz, periodic impulse noise with uniform amplitudes at equally spaced intervals is found. H. Meng et al in their paper modeled and analyzed noise effects on PLC and found that multi-carrier scheme performs better than single-carrier scheme when subjected to the observed power-line noise with non-Gaussian statistics (H. Meng *et al*, 2005)

Another paper that discusses in detail the transmission and impedance characteristics of power line in the high frequency range will be reviewed here (Masaoki Tanaka, 1998). In Japan, all household appliances are run by a single phase 100 V supply while industrial and other commercial buildings are run by three phase power of up to 200V. Measurements that were made by Tanaka were across the Toyohashi University of Technology's research buildings in the high frequency range (0.01 MHz – 100 MHz). It was found that in the 1-100 MHz range, the noise spectrum was found to fall under -90dBm and in the range between 100k to 1MHz; the noise level falls off at -40dBm to -80 dBm. In the range 10K to 100K, the noise falls off between -20 to -40 dBm. The figure below shows the noise spectrum characteristics.

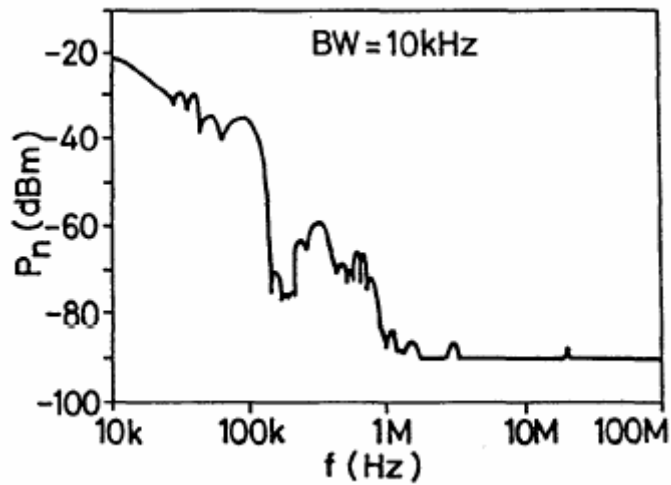


Figure 14: Noise spectrum measured in research buildings

It was found that the noise characteristics were influenced by the nature of the loads that were connected to the power line. A more detailed representation is shown in the next figure where the two spectra represent the two curves measured in July and December.

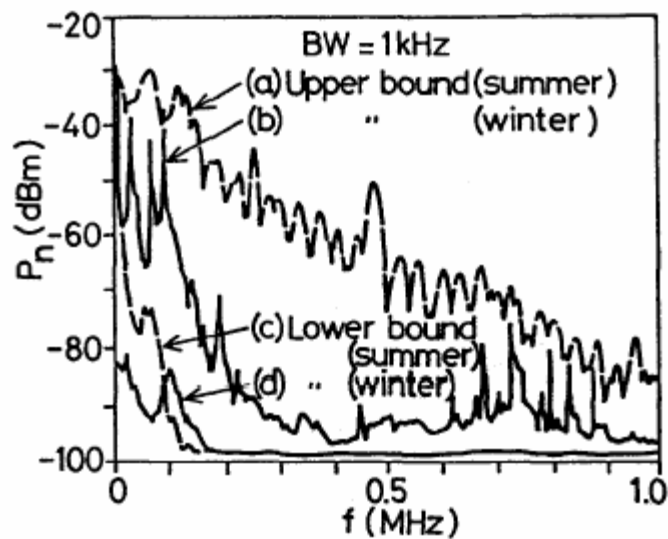


Figure 15: Noise spectrum measured at residence

The impedance characteristics of the power line environment are also investigated. The circuit that was used to measure the impedance characteristic is shown here. The relation between the input impedance of the power line and frequency is given by

$$[Z] = 0.005 * f^{0.63} \text{ ohms}$$

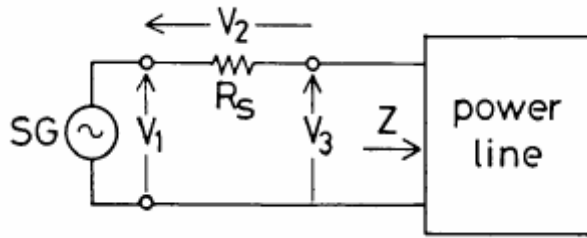


Figure 16: Circuit for measuring power line input impedance

It was found that the impedance of the power line for frequencies below 1 MHz was around 2 to 30 ohms and the impedance varied between 20 to 200 ohms in the 1 -20 MHz ranges. The input impedance of the power line with respect to frequency is as shown below.

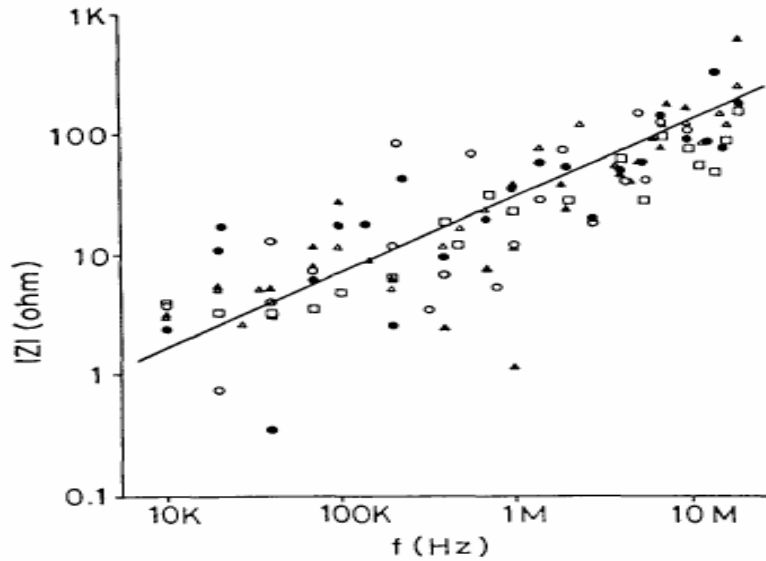


Figure 17: Input impedance of power line versus frequency

The attenuation characteristics of the power line were also investigated by means of an experiment. Assuming that there was no loss, the impedance of the sending end for open and short at the load is given by

$$Z_s = jZ_o \tan \beta l$$

$$Z_f = -jZ_o \cot \beta l$$

where Z_o is the characteristic impedance, β is the propagation constant and l is the line length. The maximum attenuation was found to be around 2 dB/m in the frequency range up to 20 MHz. The paper arrived at the conclusion that attenuation varied greatly at different places and that when the line length and frequency were comparable, the impedance of the power line is directly influenced by them.

2.7 Wideband AC Coupling

Most of the experiments that have been discussed up to now operate in the kbps range whereas in order to deliver broadband applications, Mbps range data rates are required and to achieve such data rates, wide bandwidths are required. The paper that is to be reviewed in the following section investigates data transmission in the higher data rate range. A proper coupling unit network that overcomes variation in impedance is designed. Impulse channel sounding method is used. The experimental setup consists of a signal generator that is connected to a coupler. It acts as a high pass filter with cutoff at 1MHz. The signal then enters the power network and makes an exit through another coupler that is placed at a distance. An attenuator and an LNA (Low Noise Amplifier) are placed after that in order to reduce the noise figure. The

position of the attenuator is especially crucial as it keeps the dynamic range of the LNA at such a level that reduces noise spikes (D. Liu et al, 1999). The experimental setup is as shown here.

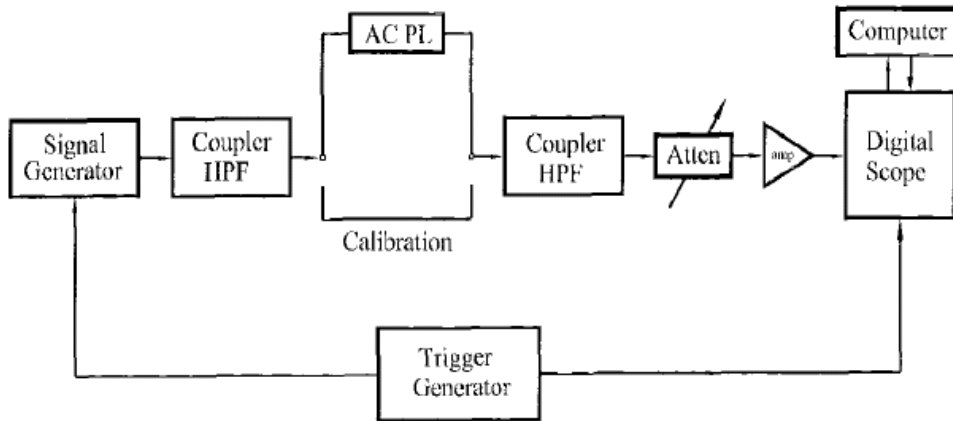


Figure 18: Experimental setup

A tedious task but nevertheless important part of the measurement setup is to go through each candidate home and make a drawing for each home. All the outlets were labeled to provide an idea of distance between each outlet pair that is measured. This becomes very useful in the link budget tool for estimating the number of outlets that a communication system can serve.

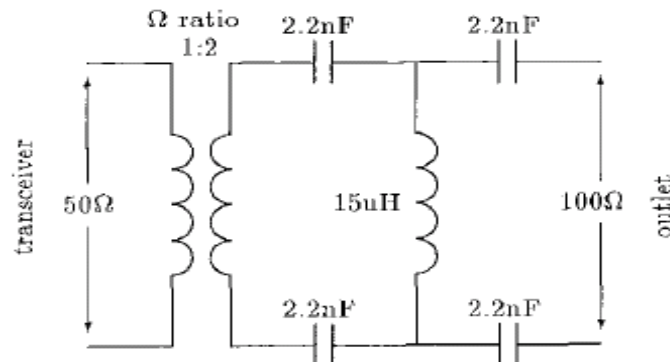


Fig. 2. Coupler circuit

Figure 19: Coupler circuit

The source level is kept fixed, while the attenuator is adjusted to ensure that the digital scope is at its maximum resolution. To minimize random noise during the measurements, up to 1000 sweeps are taken depending on power line conditions so that the actual recordings reflect averaged data. The noise measurement setup uses only the receiver coupler and the LNA low pass filter and scope.

The measurements that have been made by impulse sounding are discussed here. The figures shown below depict the resulting impulse response in the frequency and time domain respectively for a pair of outlets. There is significant pulse spreading or delay-spread. It is generally known that the AC power-line is a rugged environment and does not possess a well defined characteristic impedance. It is generally unterminated and the reflections from the terminations in such a network can cause ringing that eventually increases the delay spread.

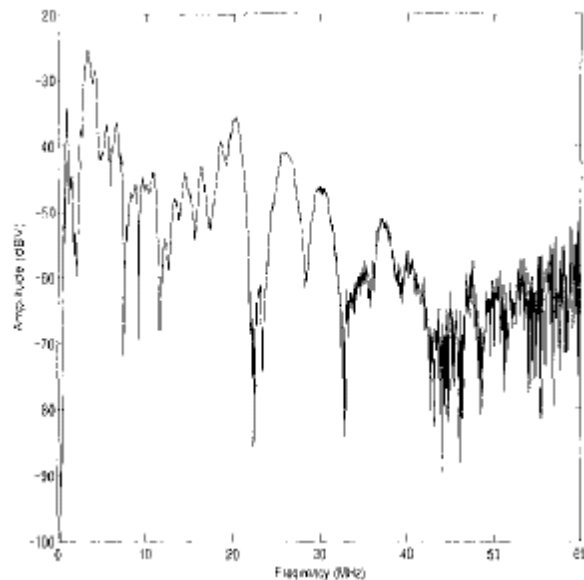


Figure 20: Impulse response in frequency domain from an outlet

In the 15-45 MHz band, there is minimum average delay and so a maximum data rate of 3.3 Mbps is obtained. So, a higher data rate needs a wider bandwidth. However, the 1-60 MHz band does not have the minimum delay spread. This is due to the fact that the AC power line is an inferior transmission medium and so a very wide bandwidth will lead to frequency response variations or dispersion. For example, a pair of outlets on different circuits, the average attenuation is around 40dB while the pair of outlets on the same circuit have attenuation in the range of 10dB.

H. Meng et al in their paper proposed a transmission line model for High-frequency Power Line Communication channel. An echo based model was used to determine the transfer function in the range of 1-30 MHz (H. Meng et al, 2002).

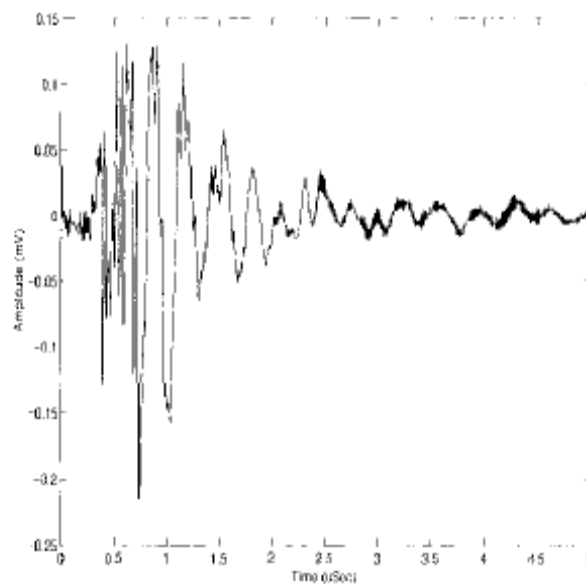


Figure 21: Impulse response in time domain from an outlet

2.8 Impedance matching in Low-Voltage PLC

The next paper that will be discussed proposes a methodology to characterize impedance matching in a low-voltage powerline network. Field measurements coming from a medium voltage (MV) network for power line communication (PLC) transmission have been shown and the frequency range 1-30 MHz is considered (Fawzi Issa, 2005).

A power budget scheme is carried out on the transmission port based on impedance measurements. The key is to know precisely the value of the transmitted power and this requires the evaluation of the impedance mismatch at the transmission port. As far as EMC is considered, it is important to have a reliable measurement method for the measurement of the transmitted power. The radiated emissions associated with the transmitted signals have to be considered regarding the transmitted power and not a pure resistive load taken as a classical reference.

At each transmission port, a source (PLC modem) is connected to a load (LV or MV networks).

$$Z_s = \bar{Z}_\ell$$

This equation shows that if there is an impedance mismatch at the emission port, it means that the total active power delivered by the source P_s will be partly transmitted to the load P_t and partly reflected P_r . So, we have the power budget equation as

$$P_s = P_t + P_r$$

P_r is negligible only if an impedance matching circuit is designed and installed between the source and the load. Finding the value of P_t is not a difficult problem if it is possible to evaluate the impedance mismatch at the transmission port. Z_s is given by the PLC modem. However, Z_ℓ is a much more complicated quantity since complex impedance in the 1-30 MHz

range has to be computed. This can be achieved by using a network analyzer. A very convenient way to evaluate the impedance mismatch consists in the calculation of the reflection coefficient s at the transmission port which magnitude is defined between 0 and 1. From the Smith chart, Z_s and Z_l are related as follows:

$$Z_l / Z_s = 1 + s / 1 - s$$

The total active power delivered by the source and the impedance of the load at the emission port is known. It is therefore easy to calculate both the active reflected and transmitted powers. The experimental network is fully described in the figure below.

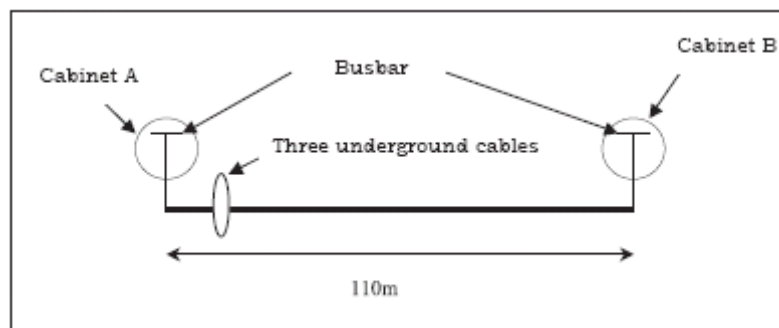


Figure 22: Experimental MV network

There is a 110m direct path of underground MV cables. A single core cable is used in this case. These cables are not energized and at the boundary, a short circuit is induced between the conductors

Two different types of path loss measurements have been carried out in this experiment. In the first type, the attenuation between Cabinet A and Cabinet B is measured without considering any impedance measurement at the injection port. It is assumed that the impedance of the network at the emission port is equal to impedance of the source. The second type of measurement is obtained using a network analyzer to measure both the magnitude and

the phase of the impedance. Various scenarios have been considered by defining several possible emission and reception ports. Moreover, in order to characterize the complete behavior of the network, the attenuation associated with the busbar and the noise level is also measured.

The figure shown below displays the measured attenuation between the two cabinets and the attenuation through the busbar versus the ambient noise level. The total active power delivered by the source is 0dBm when the impedance is 50.

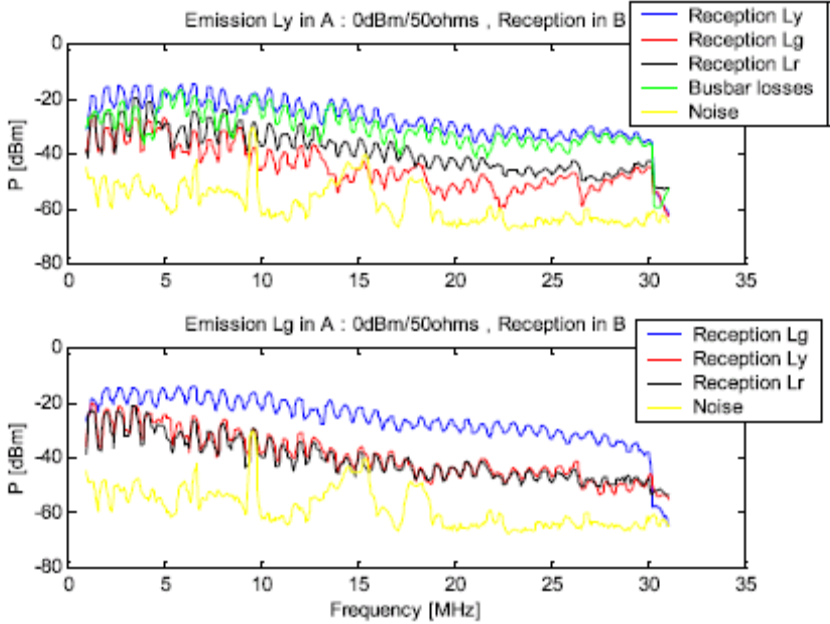


Figure 23: Measurement of network impedance

The ohmic losses associated with the busbar (green curve) are very small since these losses are very close to the attenuation obtained for the direct path (blue curve). This is probably related to the non energized state of this experimental network. In this non energized network, the phases are grounded for safety reasons. Attenuations of around 10dB have been obtained on energized network. The impedance of the short circuit located at both emission and reception

ports cannot be approximated to a pure short circuit. A very strong inductive behavior has been found for the network impedance mainly due to the serial part of the underground cables.

Joseph Nguimbis et al designed an optimized coupling unit that provided gain equalization and wide band mitigation to the effects of low impedance loads in the high frequency range. Experimental measurements were made in industrial environments in China (Nguimbis *et al*, 2002)

2.9 Design of a bidirectional impedance transformer for Low Voltage PLC

The next paper discusses the design of a bidirectional impedance transformer for low voltage power line communications. Transformer coupling circuits are used extensively in low-voltage power-line communications, because the transformer provides galvanic isolation from the power-line network and acts as a limiter when saturated by high-voltage transients. As power-line impedances are generally very low, poor power transfer is achieved because of the mismatch between modem impedance and power-line impedance. (Petrus A. Janse van Rensburg, 2005)

A properly designed coupling circuit can primarily adapt the impedance level of a certain modem to a chosen typical impedance level of the power line and subsequently be used as a bidirectional coupler for two-way communication. A 1:7 coupling transformer is designed and amplitude response measurements of the same indicate the bidirectional symmetry. The possibility of core saturation needs to be considered as the unfiltered power waveform typically has an influence of factor 10 on core flux density compared to the communication waveform. A comprehensive model, including the coupling transformer's magnetizing inductance, is used to

accurately determine the filter characteristics for low frequencies. The fluctuating power-line impedance values cause the bandwidth of the coupling filter to fluctuate when a signal is transmitted. In the receiving direction though, the bandwidth of the coupling filter stays constant as the modem impedance stays constant.

2.10 Adaptive Impedance matching in PLC

The final paper that will be reviewed in this chapter discusses an adaptive impedance matching network for Power Line Communications. PLC suffers from a relatively high BER and instability that is due to the time varying characteristics of power line. A new method is proposed that measures the current line impedance and compares it with a typical preset value, and then intuitively selects the proper parameters of matching components to make a good matching. Since there is a continuous adaptation between power line and communication equipment, the power sent out to the line and received by the receiver is maximized (Li Qi, 2004).

The power line is primarily designed for power supply and is not intended for transmitting signals. A very serious problem with PLC is the time varying characteristics of the power line. For the transmitter and the receiver, the output impedance is designed to a fixed value according to a given line impedance value.

The impedance is time varying and changes continuously and unpredictably, and the value of impedance varies too largely to ignore when the system is designed. So the transmitter and the receiver cannot match the load impedance, and there are reflections on the interfaces of the communication equipments and the power line. As a result, the power cannot be sent out by

the transmitter and also cannot be received by the receiver. This leads to the poor performance of the communication system in transmission.

The transmitter and receiver can be designed to fit a time varying load impedance. The best solution would be to adapt the interface impedance of the communication equipment to the varying power line impedance. The adaptor that will be used here is called the Auto Adapted Impedance Matching.

The figure below shows the schematic of the original system. The high-voltage capacitor couples the communication system' from the power line. The couple filter is a high pass filter. It suppresses the high voltage at power line frequency and lets the signal at carrier frequency to pass through. The transformer functions as an impedance converter and converts the impedance at power line side to the impedance at communication equipment side. When the impedance at the power line varies, the band-pass character alters obviously. The primary alteration is the attenuation, and also the character of pass band is not flat any longer. So the signal attenuates and distorts, that leads to the deterioration of system performance.

The adaptation module consists of three parts: data collecting part, calculation and control part, and matching part. Data collecting part collects current line parameters and transfers them to calculation and control part, then, current line impedance is figured out in this part. This part also compares current line impedance with typical line impedance and finds out the error between them, and then gives out a set of control signal for matching. The matching part alters parameters of itself, including inductor and variable transformer and hence the matching is achieved. As the time varying character in power line is a continuous and relatively slow process, the adaptation system is strictly real-time.

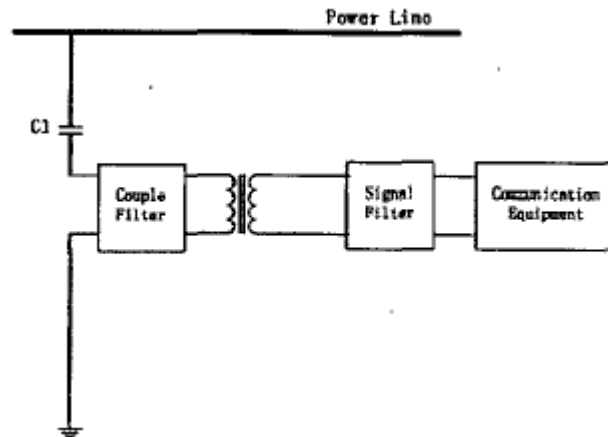


Figure 24: The original system

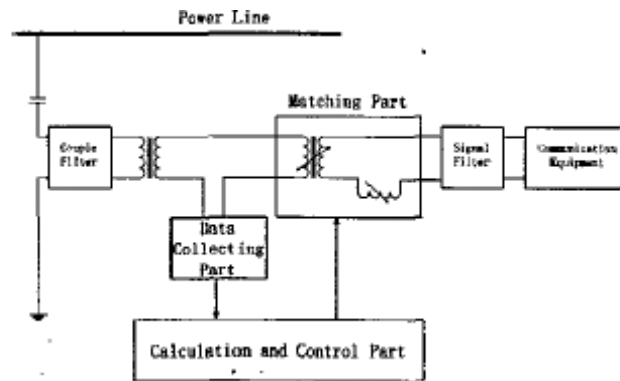


Figure 25: The system after adaptation

An adaptation model called Model Reference Adaptive System (**MRAS**) is used. When input signal is given, the reference model generates a typical output. The input is also added to the object under control and also generates an actual output. Since the actual system is different than reference model, there is an error between typical output and actual output. This error turns out to be feedback to alter the parameters of the controller and thus, the characteristics of the object under control approaches the reference model.

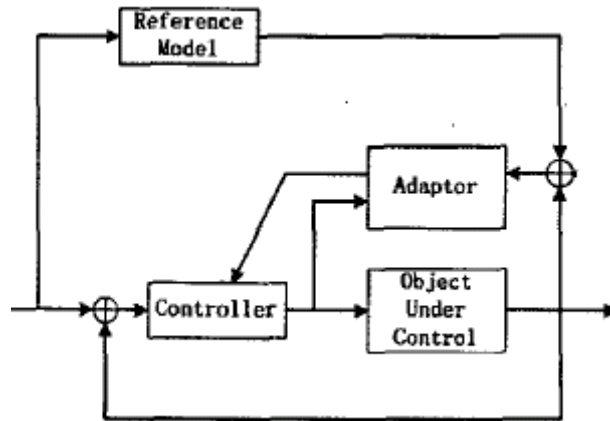


Figure 26:MRAS Schematic

It is found that during the actual measurement test, the adaptation system does have a certain effect on preventing power loss and signal distortion.

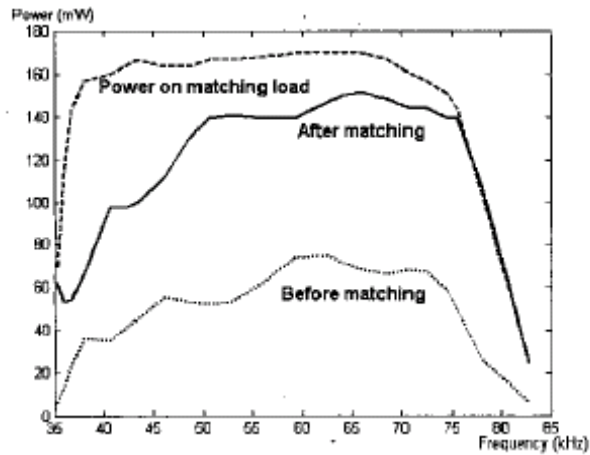


Figure 27:The network before and after adaptation

CHAPTER THREE: METHODOLOGY AND SIMULATION RESULTS

3.1 Low Voltage PLC environment

The low-voltage PLC network is an attractive innovation in the field of communication. PLC utilities can support energy distribution and provide a pipe for high-speed reliable communication traffic. However, the low-voltage electrical network is an unfriendly environment. It causes interference, has low signaling impedance and requires a highly linear operating environment (J. Nguimbis *et al*, 2004)

The impedance of the mains network at signaling frequencies is relatively low (1 to 30 ohm). The signaling impedance fluctuates as different loads are switched on during the day or over a season and is influenced by many factors such as the network parameters, load, and communication equipment location. As a result, the signaling environment fluctuates irregularly, and differs greatly from one installation to another. The transmitter must be able to drive sufficient signal into the mains network under these loading conditions. The powerline transmitter requires a highly linear coupling unit that is able to transmit carrier frequency signals with low distortion and at the same time, offer efficient protection of personnel and equipment against the effects of the power frequency voltage and transient overvoltages.

3.2 PLC Impedance matching network

Impedance matching performs a two-fold function in high frequency circuits: to enable maximum power transfer between the source and load and to tune the performance of the circuit by controlling the impedance of the source or load. Two RF Power MOS transistors BLF177 of Philips Semiconductors for HF and VHF frequency ranges have been used for the circuit. They come in a 4 leads flange SOT121 encapsulation. The transistors operate in Class-AB at $V_{DS} = 50V$ with a quiescent drain current of $I_{ds} = 0.5A$ and they have a combined Peak Envelope Power (PEP) output of 300W. The main properties at $P_o = 300W$ are:

- Power gain: 22 to 23 dB
- Efficiency: 52.5 – 61 %
- Return losses input: less than -15.5 dB
- 2nd harmonics: less than -25 dB
- 3rd harmonics: less than -16 dB
- Intermodulation distortion at $P_o = 300 W$ is less than -33 dB (NCO 8703, Philips Application Note, 1998)

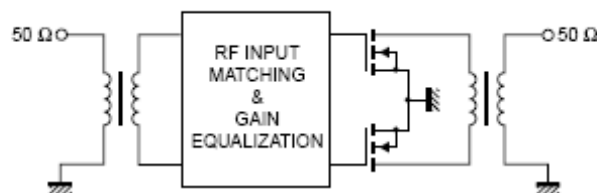


Figure 28: PLC impedance matching block diagram

The balance to unbalance transformers are applied to split the input into two out of phase ports and also add the two out of phase ports into a single ended output. A special circuit at the input takes care of matching at the input.

3.3 Amplifier Topology: Class AB Power Amplifier

The following are the salient features of the Class AB power amplifier used in the coupling unit.

- Class AB amplifier is a combination of Class A & B power amplifiers.
- Both devices conduct at the same time.
- Each device conducts for more than half a cycle but less than the whole cycle
- Class-AB operates at a constant gate voltage, a quiescent drain current that increases with drive power.
- Maximum efficiency is obtained at maximum power; theoretical maximum efficiency of a class-AB amplifier is 78.5%
- The power gain of a class-AB amplifier is between those of class-A and class-B amplifiers.
- Practical Efficiency for Class AB amplifiers is about 50%.

The following figure gives the amplifier topology that works at 300W PEP and in the frequency range 0.1-30 MHz. The input and output are to be compensated to provide the proper efficiency. The circuit matches the input impedance of each transistor to 6.25Ω of the input transformer. The matching network can be treated as the half of a double pi-section. Removing the in and output capacitance, the circuit changes into a T-section with C_i as capacitor and 2 inductances with a value of half the inductances of the double pi-section.

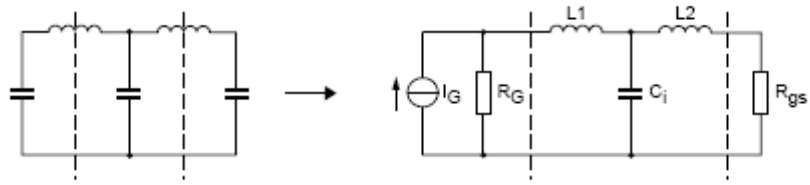


Figure 29: Input impedance matching circuit

From the data sheet, an output capacitance of 190 pF rises at full power by about 15% to 220 pF. The capacitive reactance at 28 MHz is four times R_L of 6.25Ω that leads to a high VSWR. So, the output needs to be compensated. Chebyshev filter theory and computer optimization programs are used and the output VSWR is brought down to 1.007

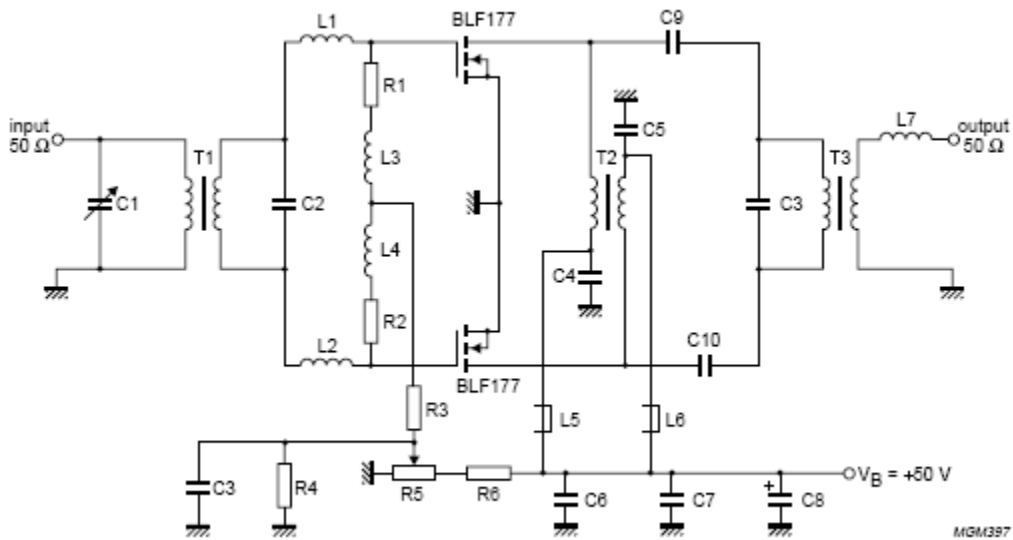


Figure 30: Class AB-power amplifier

3.4 Coupling Unit Circuit simulation

Advanced Design System (ADS) has been used to simulate the circuit as it has enhanced features which can model the circuit accurately. Performing DC analysis of the MOSFET to view the operating characteristics would be the first step in any circuit simulation. In ADS, the component library does not support the Philips RF Power transistor BLF177. The DC curves of the transistor (BLF177) are as shown below.

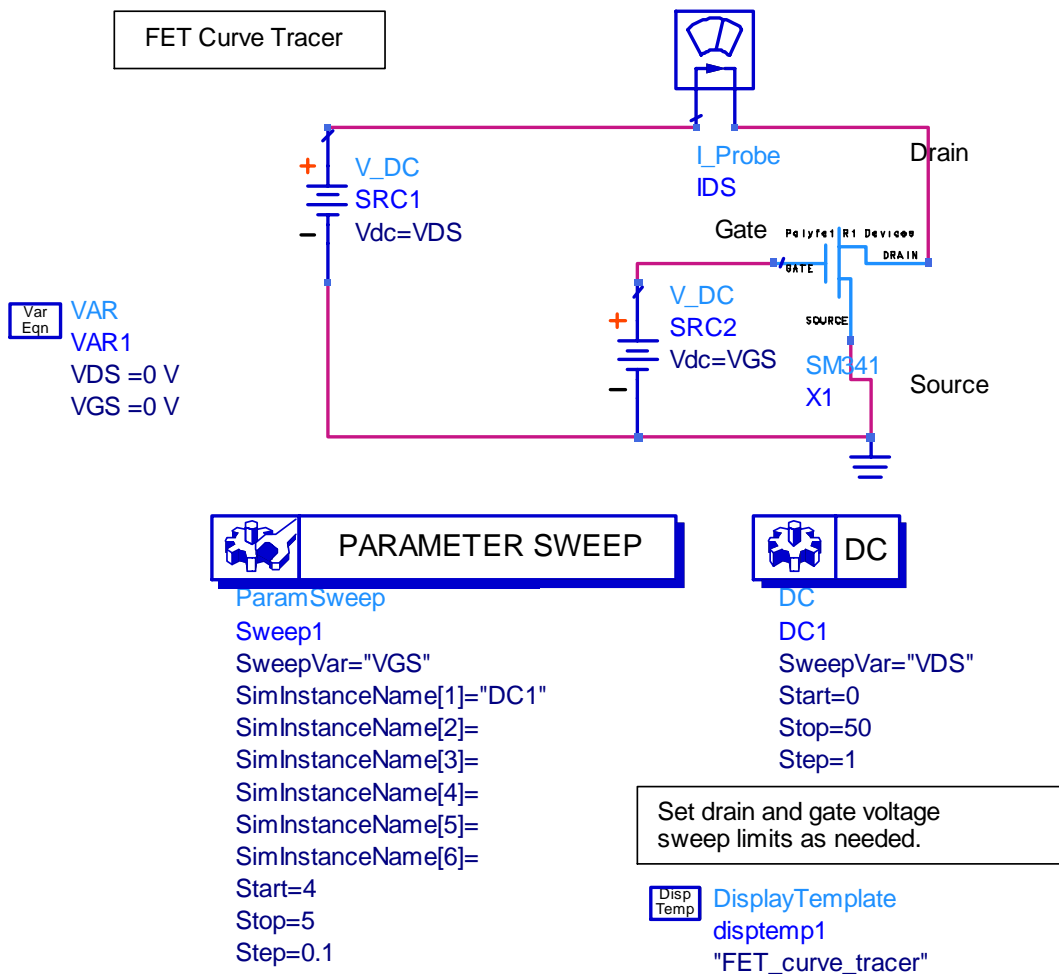


Figure 31: DC curve tracer

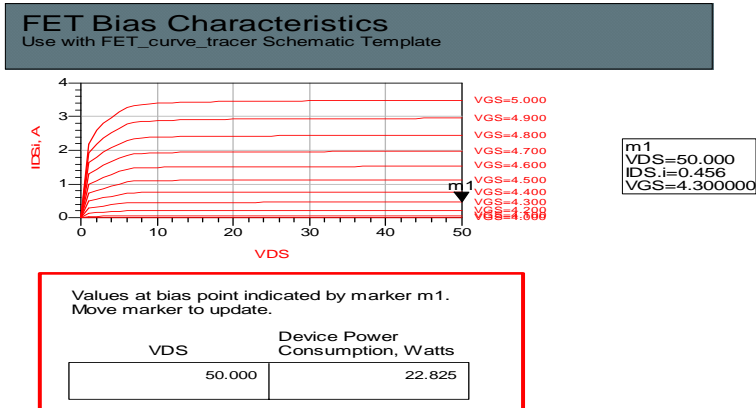


Figure 32: FET Bias characteristics

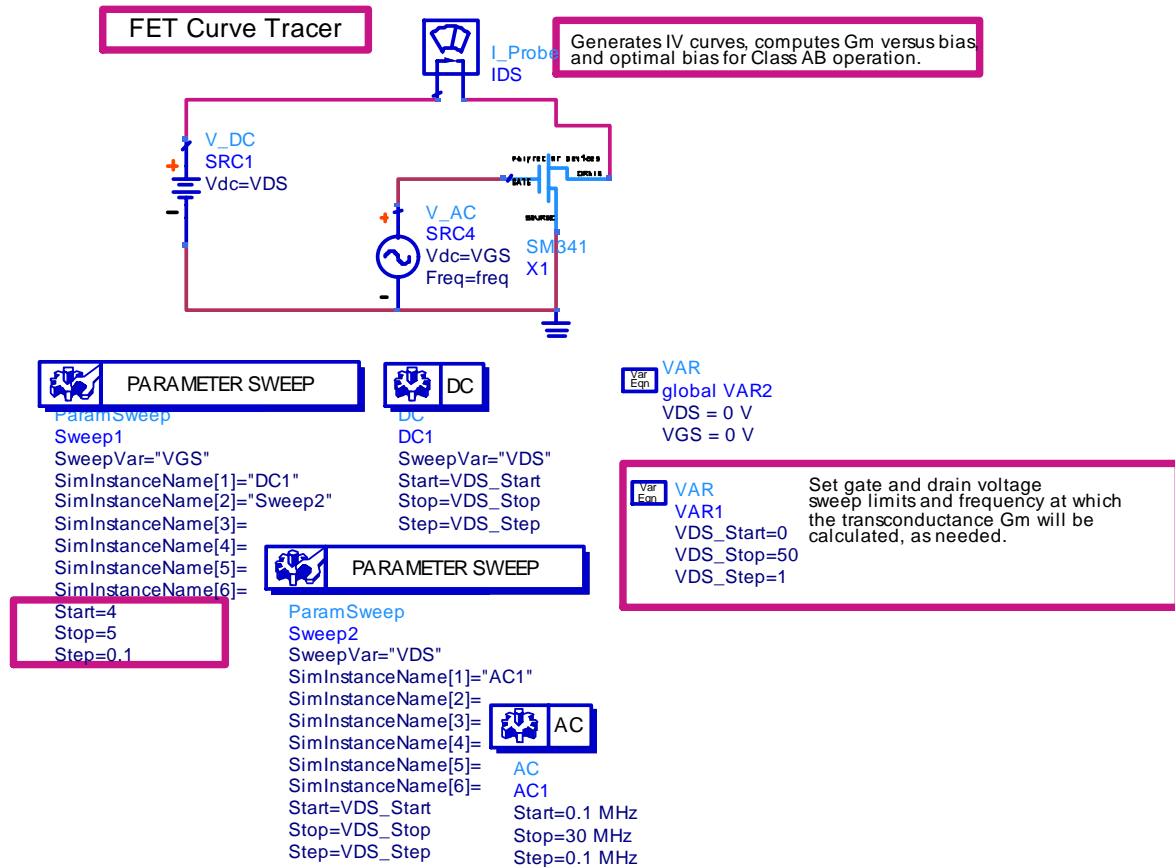


Figure 33: MOSFET I-V characteristics setup

The DC curve tracer technique in ADS can also be used to obtain other curves like gm (transconductance) versus Drain-source voltage (Vds), transconductance versus gate-source voltage, transconductance versus drain-source current and so on. The curves obtained for each of these cases are as shown below.

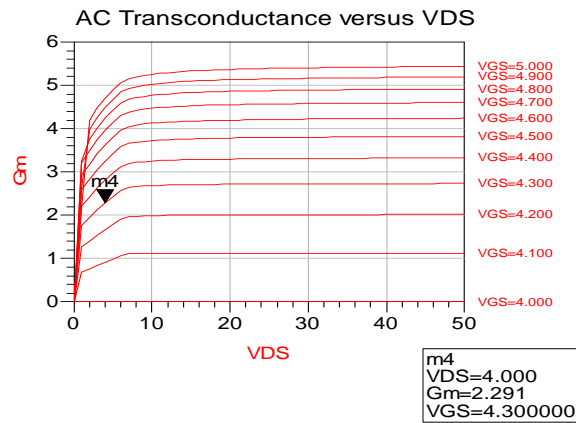


Figure 34: Transconductance (gm) vs. Vds

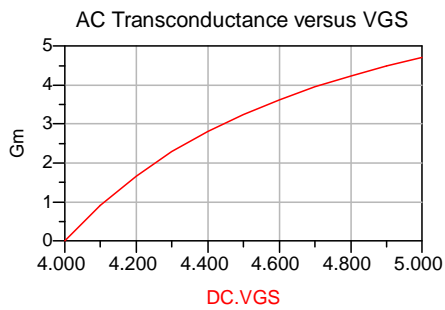


Figure 35: Tran conductance versus Vgs

3.5 Single tone Harmonic Balance simulation

Harmonic balance is a frequency-domain analysis technique for simulating nonlinear circuits and systems. Harmonic Balance Simulation calculates the magnitude and phase of voltages or currents in a potentially nonlinear circuit.

- Compute quantities such as P1dB, third-order intercept (TOI) points, total harmonic distortion (THD), and intermodulation distortion components.
- Perform power amplifier load-pull contour analyses
- Perform nonlinear noise analysis
- Simulate oscillator harmonics, phase noise, and amplitude limits

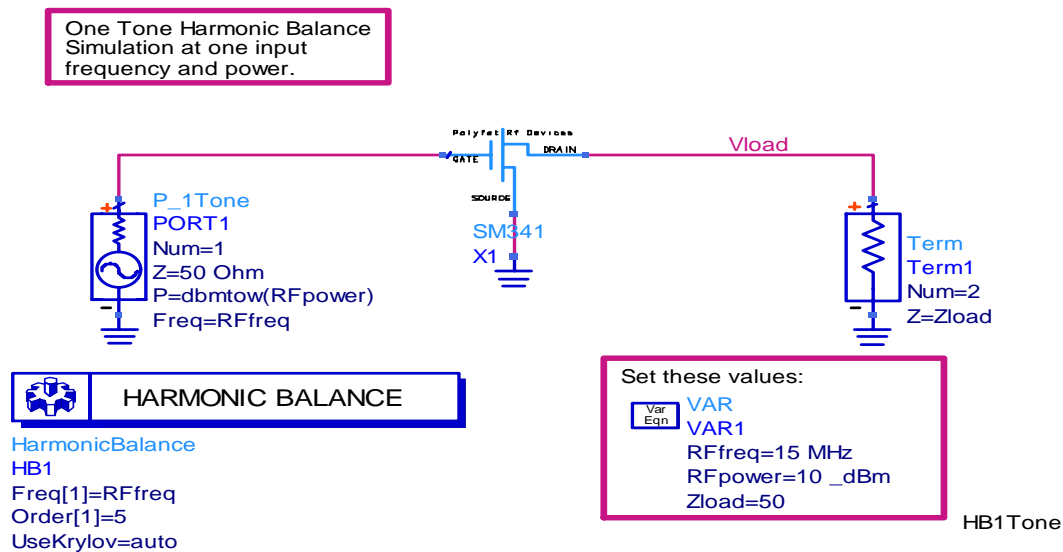


Figure 36: Single-tone Harmonic Balance simulation

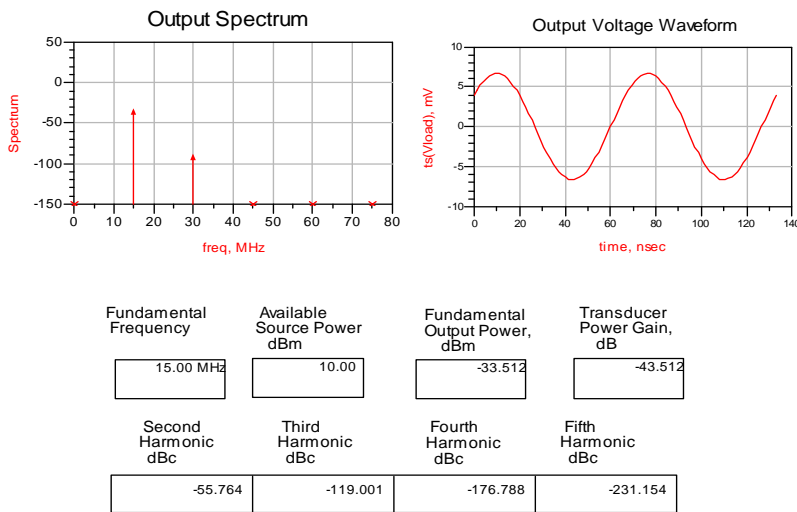


Figure 37: Output spectra and output voltage waveform

3.6 Single-tone Harmonic Balance simulation with swept frequency

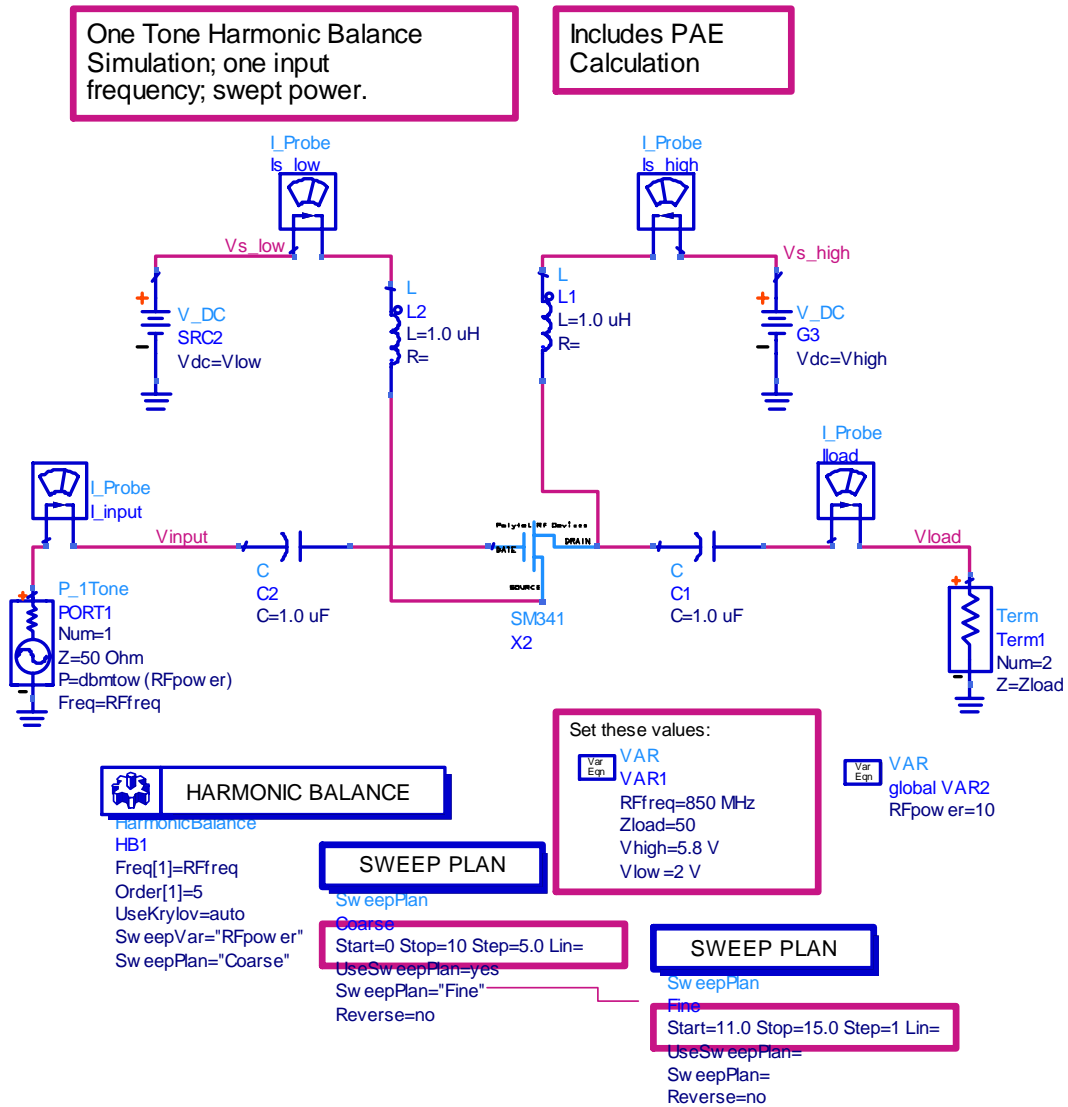


Figure 38: Single tone Harmonic Balance simulation with swept frequency

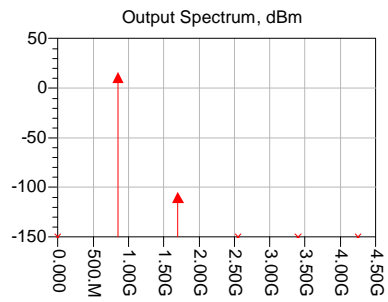


Figure 39: Output spectra

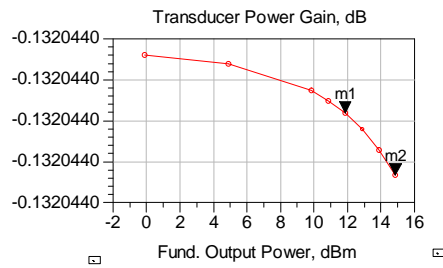


Figure 40: Transducer power gain

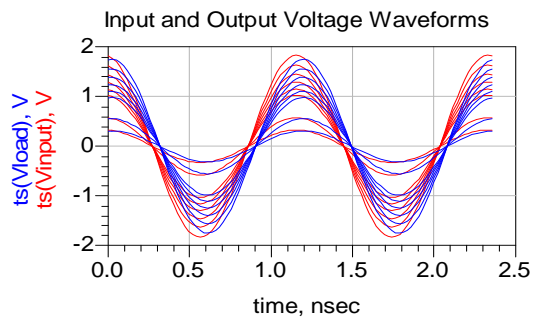


Figure 41: Input and output voltage waveforms

3.7 Double-tone Harmonic Balance simulation

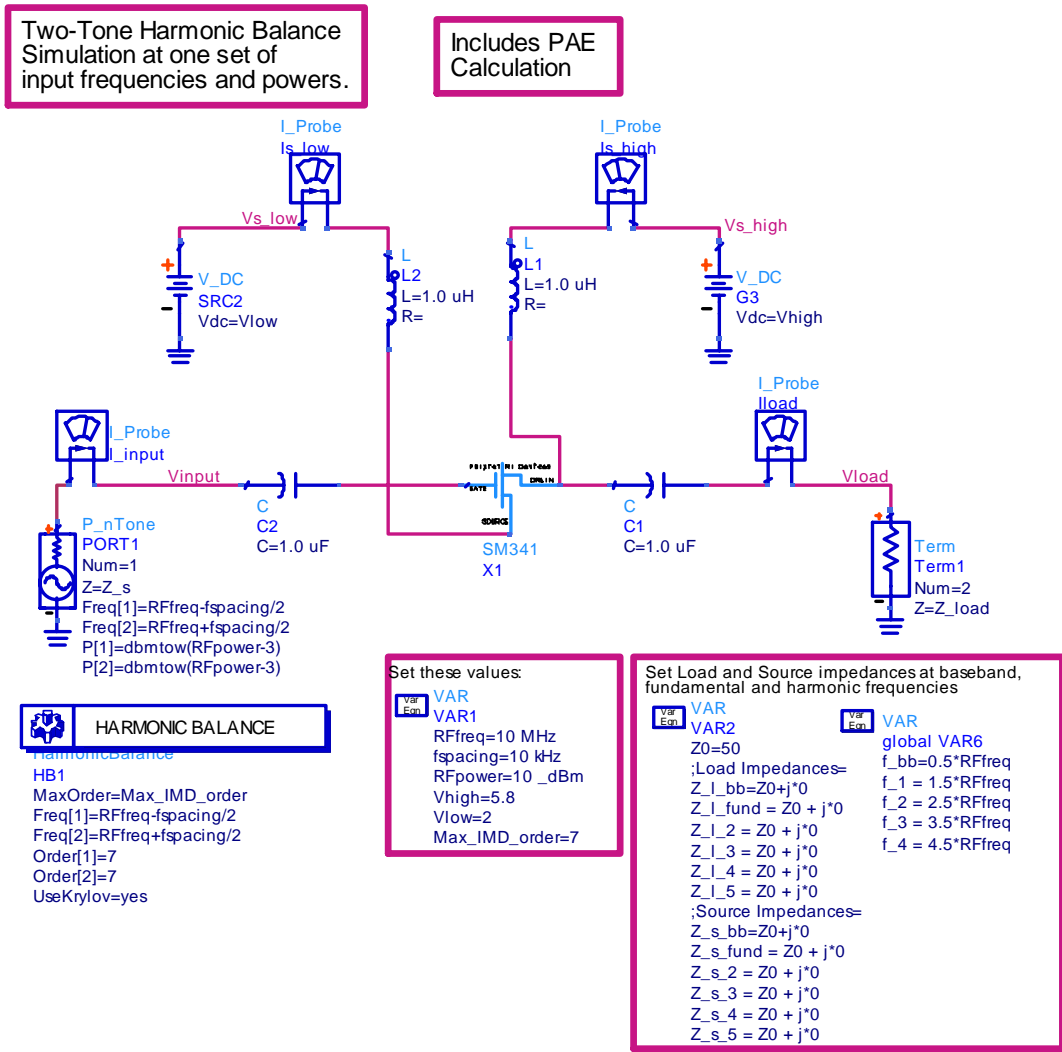


Figure 42: Double tone Harmonic Balance simulation

Low and High Side Output TOI Points, dBm		Low and High Side Input TOI Points, dBm	
44.530	44.539	45.393	45.401
Low and High Side Output 5thOI Points, dBm		Low and High Side Input 5thOI Points, dBm	
40.703	40.708	41.566	41.571

These become invalid as the amplifier is driven into compression. If the low and high side TOI points do not agree, try increasing the order of each tone and/or the Max_IMD_order.

Figure 43: TOI (Third Order Interference) results

3.8 AC circuit simulation

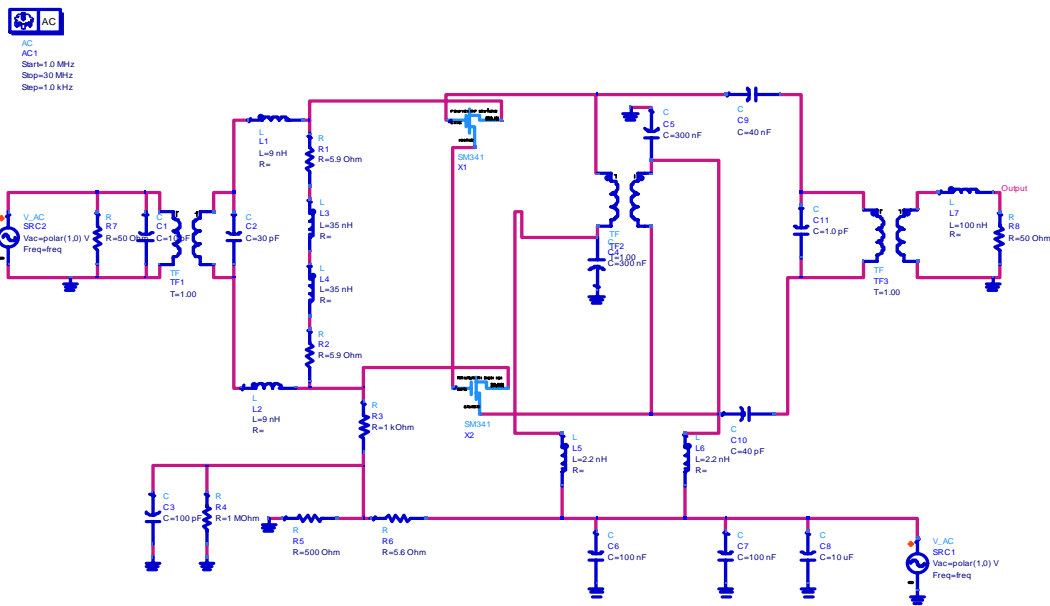


Figure 44: AC circuit simulation setup

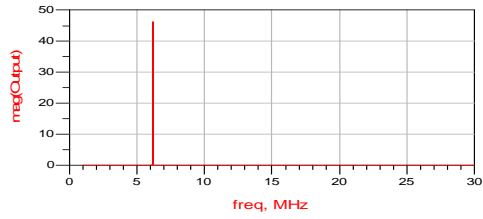


Figure 45: Magnitude versus frequency

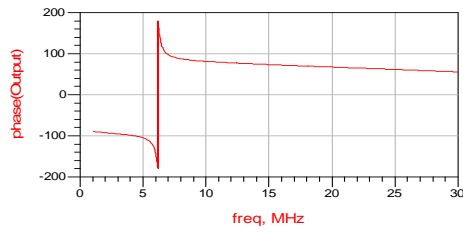


Figure 46: Phase versus frequency

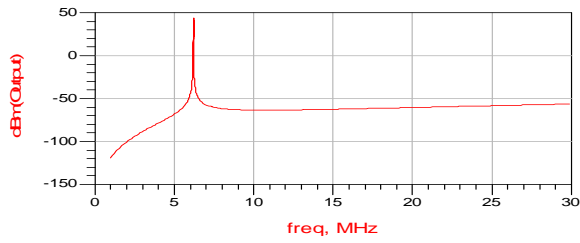


Figure 47: Magnitude (dB) versus frequency

3.9 Transient simulation

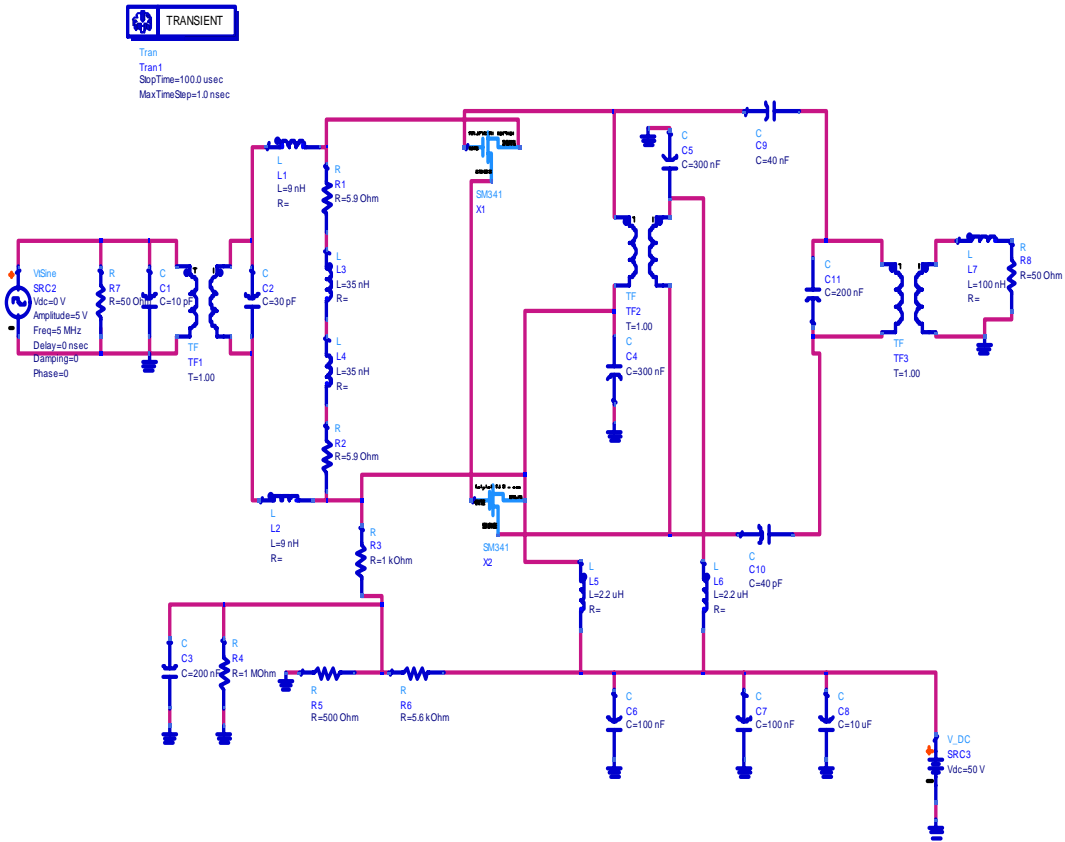


Figure 48: Transient simulation setup

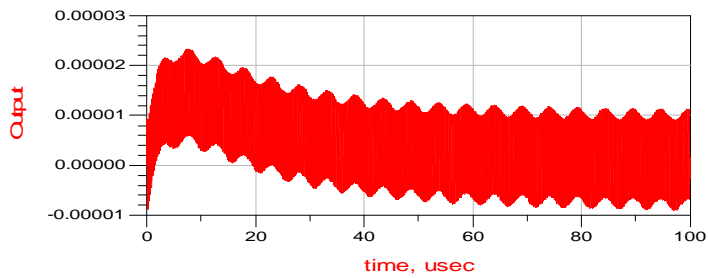


Figure 49: Transient output waveform

CHAPTER FOUR: RESULTS, CONCLUSION AND FUTURE WORK

4.1 PLC Coupling Unit

The PLC experimental prototype is fabricated in accordance with the design procedure that has been dealt with in the third chapter. The components have been obtained from a variety of places that include Ferroxcube, Mouser Electronics and Newark. The layout for the prototype was made using OrCAD and the toner transfer method was used to transfer the layout onto the copper board.

After the layout is transferred onto the board, the board was etched using 10% ferric chloride mixed with water. The solution is stirred with the help of a magnetic stirrer and the copper board is placed into the solution. The unwanted copper is etched leaving only the traces that are needed.

The components are then soldered onto the board one by one. Copper wires are wound around the input and output transformers according to the specifications that have been given in the datasheet. The trimmer at the input has a capacitance rating of 5-57 pF. According to the data sheet, the capacitor has to be tuned to 15 pF in order for the circuit to function effectively. The cermet potentiometer forms the voltage divider network, delivering a gate voltage of 7.5 volts approximately. The potentiometer has a resistance rating of 500 Ω and the pull-up and pull-down

resistors have been adjusted to be around $100\ \Omega$ and $400\ \Omega$ respectively. The etched layout and the fabricated prototype of the coupling unit are shown in the following figures.



Figure 50: Etched layout of the coupling unit

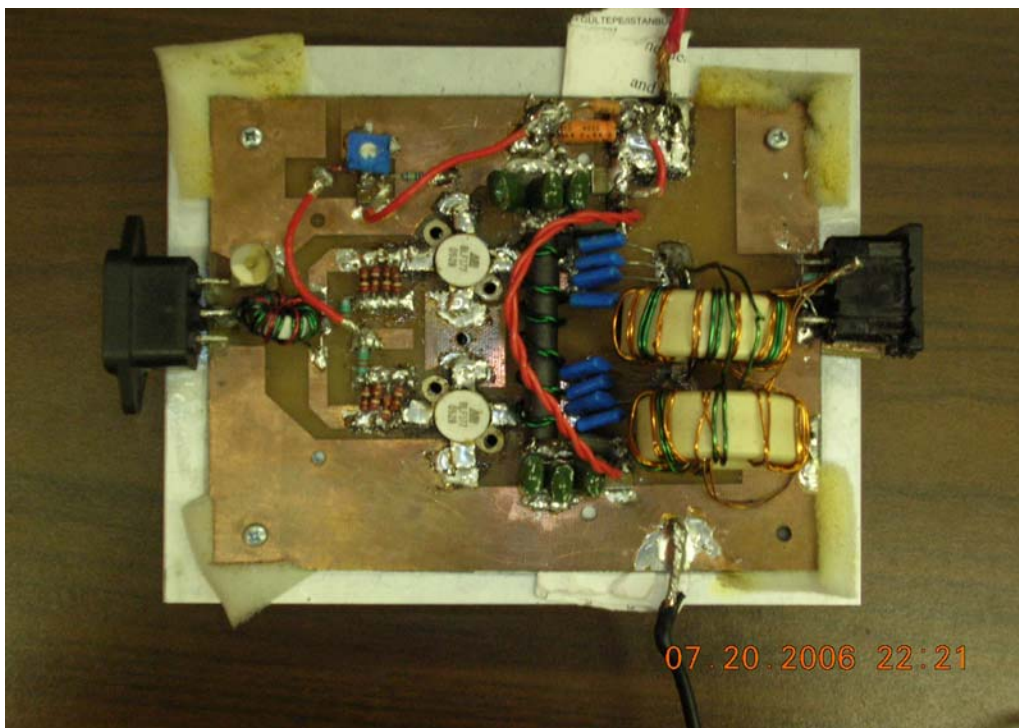


Figure 51: PLC Experimental prototype

4.2 PLC Experimental setup

The figure below is an experimental setup that shows the how the coupling unit is incorporated into the PLC communication scheme.

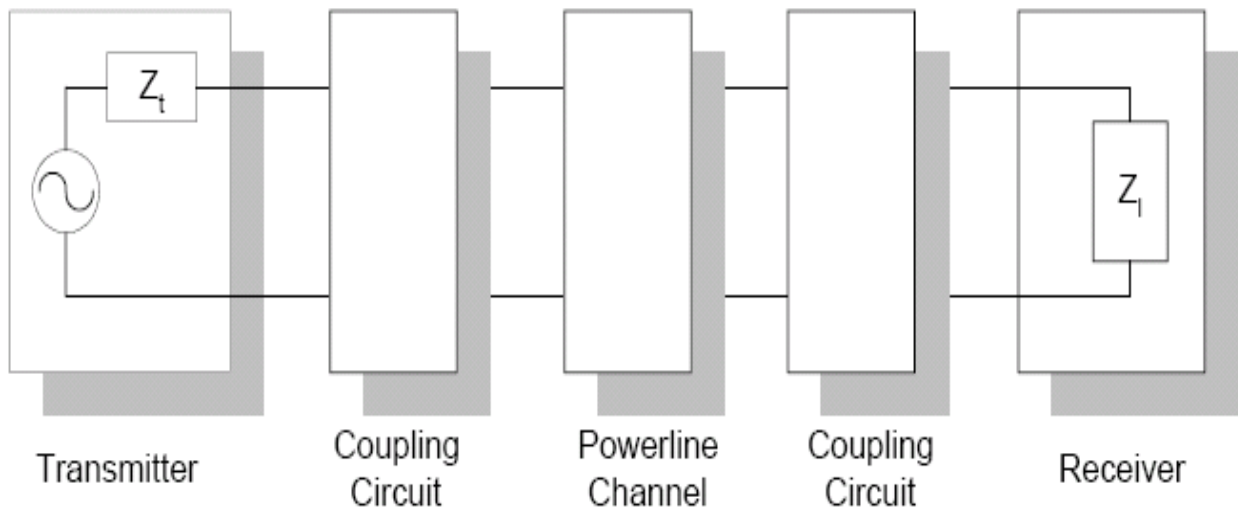


Figure 52:PLC Experimental setup

This shows a digital communication system using the power-line as a communication channel. The transmitter is shown to the left and the receiver to the right. Important parameters of the communication system are the output impedance, Z_t , of the transmitter and the input impedance, Z_l , of the receiver. A coupling circuit is used to connect the communication system to the power-line. The purpose of the coupling circuits is two-fold. Firstly, it prevents the damaging 50 Hz signal, used for power distribution, to enter the equipment. Secondly, it certifies that the major part of the received/transmitted signal is within the frequency band used for communication. This increases the dynamic range of the receiver and makes sure the transmitter

introduces no interfering signals on the channel. The coupling unit however did not perform according to expectations as the transistors used in the experiment got burnt and the cost of replacement was found to be too expensive to meet the desired objective. The experimental transmitter and receiver boards that were supposed to be used could not be incorporated into the final setup.

4.3 Future work

The coupling unit is perhaps the most important block in a PLC setup and an experimental prototype that works in the high frequency range has been simulated and fabricated to verify its performance. The coupling unit can be used to transmit digital and analog data over power lines and hence can effectively serve as a High pass filter (HPF), mitigating the effects of the ac signal that operate over the power lines.

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