ANALYSIS OF POWER LINE COMMUNICATION CHANNEL MODEL USING COMMUNICATION TECHNIQUES

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Varinder Pal Singh

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr. Hongxiang Li
Co-chair

Dr. Bei Gou
Co-chair

Dr. Chao You

Dr. O. P. Yadav

Approved:

03/19/2013	Dr. Rajendra S. Katti
Date	Department Chair

ABSTRACT

With the advent of technology, human dependency on power (electricity) and communication has grown beyond leaps and bounds. Many efforts have been made to continuously improve and increase the efficiency in both areas. Power Line Communication (PLC) is a technology where power lines or transmission lines are being used for communication purposes along with transmitting electrical energy. Because the power grid is already in place, the PLC has the obvious advantage of reducing communication infrastructure cost. However, the power grid is designed optimally for power delivery (not the data). The power transmission line generally appears as a harsh environment for the low-power high-frequency communication signals. In order to evaluate the performance of PLC, this paper simulates a practical multipath power line communication channel model and provides the Bit Error Rate (BER) vs signal-to-noise ratio (SNR) curves for orthogonal frequency division multiplexing.

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LIST OF ABBREVIATIONS

AMI	Advanced Metering Infrastructure
AWGN	Additive Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BPL	Broadband over Power Line
BW	Band Width
CP	Cyclic Prefix
CENELEC	European Committee for Electrotechnical Standardization
DG	Distributive Generation
Rx	Receiver
DTL	Digital Transmission Line
DS	Distribution Substation
FFT	Fast Fourier Transform
FDM	Frequency Division Multiplexing
HV	High Voltage

IFFT	Inverse Fast Fourier Transform
IEEE	Institute of Electrical and Electronics Engineering
ISI	Inter Symbol Interference
LV	Low Voltage
MV	Medium Voltage
OFDM	Orthogonal Frequency Division Multiplexing
PSD	Power Spectral Density
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
SG	Smart Grid
TS	Transmission Substation
Tx	Transmission

1. INTRODUCTION

Power grid [6] or Electrical grid is an interconnected network of wires and other components, delivering power from the point of generation to the end user. Major operations concerned with the aforementioned are:

- Power generation
- Power transmission
- Power distribution
- Power control

It is evident from the 2003 blackout [1] that existing power grids have severe drawbacks, which cannot be ignored. These drawback aren't the only concerns in themselves, they present a national security threat as well. The central power generation and distribution system, first designed by Nicole Tesla, is based on a cascading design and has not been updated ever since its inception. Failure in one part of the grid leads to failure of other parts due to its cascade design. Other major reasons which demand the upgrading of the grid is the transmission and distribution loss of power while transferring it to the end user. As of today, one cannot afford such losses, seeing as the demand of power supply is consistently increasing.

Another way to cope with the high power consumption rate is to implement the Variable demand and supply [2] method. An end user - domestic, commercial or industrial - can request an increase or decrease in the power supply depending upon their current or future load requirements. Variable demand and supply allows the power distribution system to efficiently channel the power to areas with lower requirements as well as those with higher requirements. Inclusion of alternative sources of energy contributes to clean energy and plays a vital role in energy management. As more and more renewable sources are included, power grids not only have to deal with bidirectional flow of current, but also variable power supply in the region. Complexity of the existing grid is increased by manifolds when alternative sources of energy like solar and wind energy are added to the power grid. Effective implementation of the power grid with additional functionalities, improved reliability and enhanced security requires a systematic and well established communication system.

The said communication network can be set in two ways. The first approach is to install a communication network parallel to the grid using a wired/wireless medium. The second approach uses existing power cables for data transmission, which serves a dual purpose of controlling the network as well as internet access through power lines. The biggest advantage in pursuing power line communication is to utilize the existing power grid network, which can significantly reduce the cost of adding a new infrastructure to the system. Additionally, PLC can provide internet access for rural areas. However, as power grid cables were designed for electrical current, the power transmission line acts as a harsh environment for data signals, which may yield lower throughput or higher error rate at the receiver’s end.

2. BACKGROUND AND LITERATURE REVIEW

The Smart Grid (SG) supported by communication network and renewable sources of energy tries to address concerns raised by the traditional power grid.

2.1. Smart Grid

The Smart Grid is the modernization or up-gradation of the current power grid. SG provides power along with two way digital communication to control home appliances to save energy, reduce the cost, and increase the reliability and transparency. In this comprehensive paper, introduction to and communication over power line channels is discussed. Smart Grid implements changes to the traditional grid including some major changes such as Distributive power generation [6], Role of Communication and the concept of Advanced Metering Infrastructure (AMI) [4] [5]. These new meters account for various advantages over traditional meters, becoming an effective communication interface between the grid and the consumer. The purpose of AMI is to utilize domestic, renewable and non renewable power sources, and share them with consumers via an internet-style smart transmission grid. With new policies, innovative technologies and infrastructure upgrades, the Smart Grid is poised to change the way we go about our lives.

Smart Grid aims to achieve a wide range of prospects, ranging from automated control of appliances at home to an overall reliable, secure and flexible grid. It will benefit both the power supply companies and the end user. There will be a reduction in the peak load thanks to a demand-based supply, the inclusion of renewable sources, intelligent devices and an adaptive grid.

2.2. Traditional Grid to Smart Grid

The existing power grid has grown old and needs an extensive upgrade and modernization. Grid failure is not only a mere inconvenience but poses national security threat and serious economic losses.

Smart Grid provides elegant, eco-friendly and efficient solutions to most of the problems posed by current power grid. A strong communication network acting as a backbone of the power grid makes it a more robust system. Inclusion of distributive generation reduces the peak load on central power generation and allows the grid to separate itself from affected section of the grid. Following the trend of digitization, electrical network is digitized from analog version under Smart Grid. Power and information flow in current power grid follows a broadcasting pattern with generators as starting point and domestic user as end point. Smart Grid provides power along with two way digital communication to control home appliances to save energy, reduce cost, increased reliability and transparency. The following introduction discusses some fundamental features of Smart Grid. Advanced Metering Infrastructure (AMI), accounts various advantages over traditional meters by becoming an effective communication interface between grid and consumer. Following are some features of AMI:

- Remote meter reading

- Control of appliances through remote sites

- Live tracking of electricity charges and current load

- Programmable duration and timing of device operability

Smart Grid contributes to clean energy by including alternative sources of energy. Inclusion of alternate sources like wind mills and solar panel would reduce pressure off the thermal power units. Distributive power generation is a system in which power consumed by users is generated at various locations rather than traditional central units. The concept of Net metering [7] allows the customers to sell extra power generated from privately owned solar panel/wind mill/vehicle battery to the grid. The opposite flow of electricity from consumer to grid rolls the meter in reverse direction reducing the number of already consumed electrical units. A customer is only charged for net units used, obtained by subtracting units given to grid from units consumed by using electricity from grid.

A strong communication system provides reliable and efficient platform upon which Smart Grid is based. As in previous sections we discussed the AMI and communication between user and grid proving how vital communication is for existence of Smart Grid. Communication in Smart Grid is not only responsible for notifications or reminders but also includes software based transmission, control, re-routing algorithms, fault recognition and self healing.

It is required to understand existing power grid architecture to make some significant moves in Smart Grid. Figure 1 explains basic distribution characteristic of existing power grid. Power is generated and transmitted at very high voltage from power plant to transmission substation (TS) then it is down converted and brought at medium level voltage to distribution substation (DS) and control center [8]. Here again power is down converted to low level voltage to make it suitable for user utilities. The flow of current in different levels poses some challenges while designing effective communication.

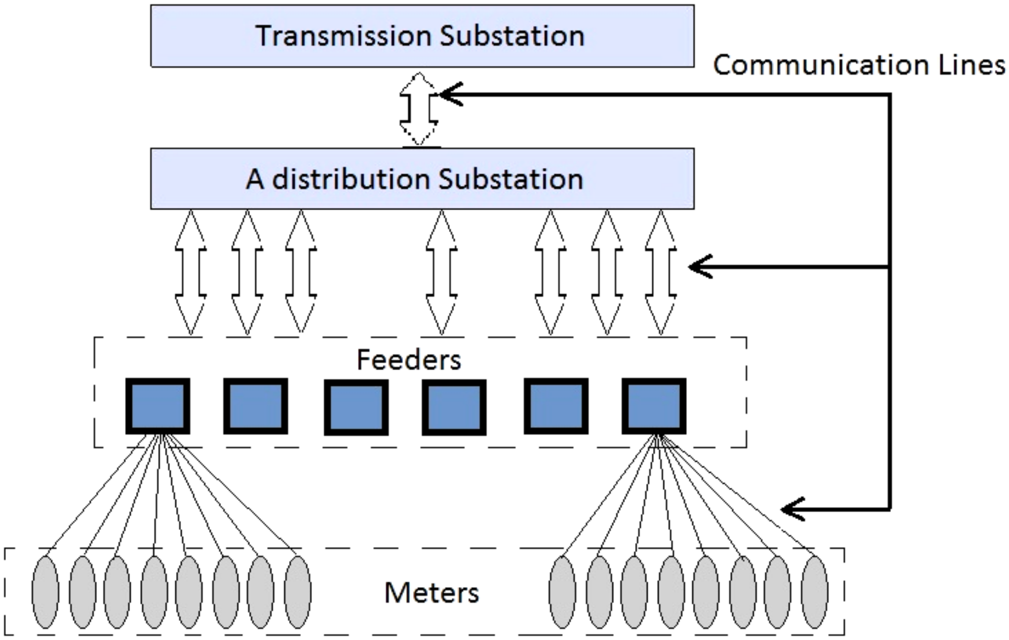

Figure 1. Diagram showing distribution of power from TS to end user [8]

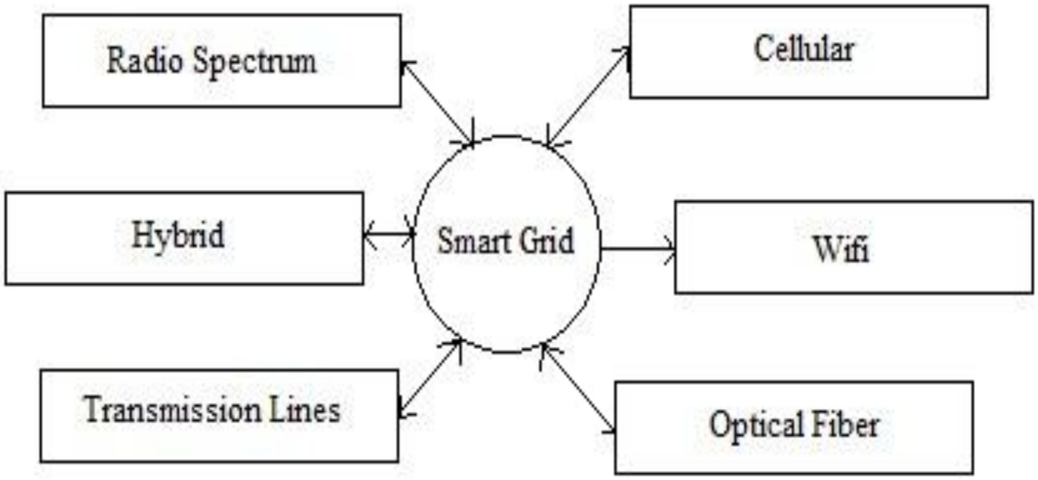

Figure 2. Communication alternatives in Smart Grid

The Figure 2 emphasizes the mode of communication within smart grid. Communication media act as interface between energy source, distribution system and consumer entities. Smart

Grid comes up with option of joining all transmission interfaces directly to the sources or can be controlled by central grid. The key concept is that all interactions between transmission interfaces and consumers are multi-directional i.e. uncommon to traditional grid now that users can also participate in reverse direction. Communication infrastructure is laid over physical infrastructure of existing grid; doing so achieves automation, robustness and efficient power grid.

By designing communication architecture to support Smart Grid, one can choose from currently available communication technologies; among wireless, wired/cable, cellular, or power line itself. Each has different advantages and disadvantages even hybrid combination of them could be used.

3. PLC (POWER LINE COMMUNICATION)

PLC also known as BPL (Broadband over Power Line) uses power lines as a medium for achieving effective bidirectional communication along with electric current flow. The concept of communicating through PLC is quite old but not brought into use on massive scale for commercial purpose. Power companies have been using this service and keeping it restricted to them only.

There are several reasons that hinder PLC from being a unanimous choice as communication medium. The first and foremost reason is that power reaches to the user from the point of generation via three stages. Sustaining the data signal through three different voltage levels (HV, MV, LV) is complicated and costly affair. At the same voltage level PLC allows communication while maintaining the quality well above the minimum threshold. Another disadvantage of PLC is that a data signal injected to power line could not pass through transformer. The use of bypass devices across transformers increases the complexity and adds to overall cost. Data signal is separated before the transformer instead of going through it and again injected to back to the power line. Significant transmission and distribution loss of power lines is another characteristic which makes PLC a secluded option. A clique is produced when a device is switched ON or OFF in a network. The Impulsive noise depletes the signal quality by introducing noise in the system. As power lines are not insulated, at high frequencies they act as an antenna hence interfering with signal being generated from high tension wire in close vicinity. Some factors discussed above prohibit PLC from becoming a complete mature communication network for Smart Grid [9] [10]. Some architecture also has been proposed for Smart Grid using PLC based upon packet oriented approaches [11].

3.1. Noise in PLC

A PLC could be categorized as follows:

- Narrow band PLC (<450KHz)
- Wideband/broadband PLC (~MHz)

The last mile power line, also known as low-voltage (LV) power lines, is a power transmission cable connecting substations to domestic houses. The source of noise at LV can be internal (inside the power network) or external (outside the power network). A detailed classification of the power line noise is listed as follows [12]:

- Colored Background Noise: Appliances and components operating at low power, collectively generates noise with relatively low power spectral density (PSD).
- Narrow band noise, mostly amplitude modulated sinusoidal signals caused by ingress of radio broadcasting stations.
- Periodic impulsive noise asynchronous to the main frequency, which is mostly caused by switched-mode power supplies.
- Periodic impulsive noise synchronous to the mains frequency, components like rectifier diodes, transistors whose cut off voltage and threshold voltage leads to switching actions in synchronous to frequency of mains power.
- Asynchronous impulsive noise, which is caused by switching transients in the power network.

Collective noise [13] is the sum of all the noise types mentioned above. Colored Background Noise and Narrow Band Noise are considered as background noise which uniformly spread throughout the spectrum, as their rate of change of magnitude is very slow. On the contrary, the last three are termed as impulsive noise since their amplitude changes rapidly.

Background noise is considered to be Additive White Gaussian Noise (AWGN) W_k for PLC analysis [14]. The impulsive noise is given by:

$$i_k = b_k * g_k \tag{1}$$

where, b_k is the Poisson process which is the arrival of the impulsive noise, g_k is the white Gaussian process with mean zero and variance $2\sigma^2$**.** That is Gaussian noise of magnitude varying up to 35 dB and is distributed among data bits complying Poisson distribution. b_k is the probability of getting hit by noise and g_k is the random variable denoting the varying amplitude of noise. The total noise n_k is given by:

$$n_k = W_k + i_k \tag{2}$$

$$n_k = W_k + b_k * g_k \tag{3}$$

Arrival of the impulsive noise follows the Poisson process with a rate of *R* units per second, so that the event of *k* arrivals in *t* seconds has the probability distribution as:

$$p_k(t) = e^{-\lambda t}(-\lambda t)^k/k! \tag{4}$$

Let a_k be the received signal, and then the transmitted signal r_k is given by:

$$r_k = a_k + n_k \tag{5}$$

In case if the modulation technique used is OFDM with BPSK as bit modulation, received signal could be characterized with the expression;

$$r_k = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} a_m e^{\frac{j2\pi mk}{M}} + W_k + i_k \qquad k = 0,1,2,3 \ldots.,M-1 \tag{6}$$

where, M is number of subchannels/subcarriers and a_m is (+1,-1) BPSK symbol.

This section discussed mathematical model of noise characteristics involved in PLC. Note should be taken that only noise is considered here. There are several other characteristics which could deteriorate the bit sequence such as type and material of wires used for transmission lines, age of power lines and interference from other products operating in same frequency range.

3.2. Multipath Channel Model

In Power line transmission the propagation of data signals do not follow single path or uni-path, but they follow a multipath [15] following a pattern very similar to wireless signals involved in cellular transmission. Power grid (LV) is a single central transmission line with shooting stems terminating at the end users place, as shown in Figure 3. T_X is the point of transmission (substation/service provider) and R_X is point of receiver (automated meter, customer or other appliances).

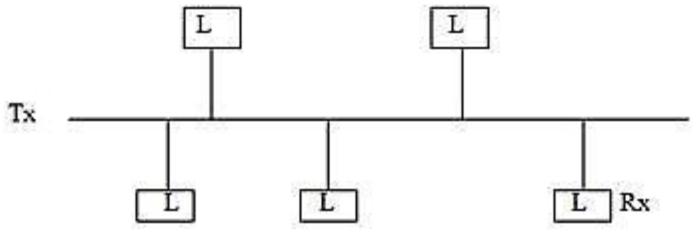

Figure 3. Typical topology of end mile transmission line in power grid

A small section of Figure 4 could be singled out to review multipath propagation of signal.

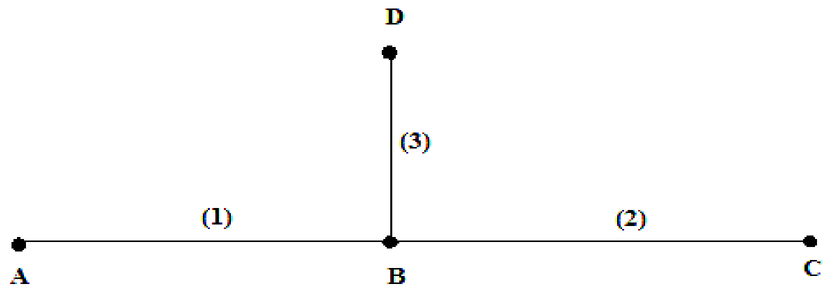

Figure 4. Multipath propagation of signal from D to C

Let D be the point of transmission and C be the point of receiving. Signal generated at point D could take following possible routs:

1. D – 3 – 2 – C
2. D – 3 – 3 – D
3. D – 3 – 1 – 3 – D
4. D – 3 – 1 – 1 – 2 – C

Expressions mentioned here list the different propagation routs. Signal power and BER of received signal depends upon the path followed and the length of the path. Multipath propagation is also responsible for delay (τ_i) in PLC, which is given by:

$$\tau_i = \frac{d_i\sqrt{\varepsilon_r}}{c_0} = \frac{d_i}{v_p} \tag{7}$$

d_i is the length of path, c_0 is speed of light and $\sqrt{\varepsilon_r}$ is dielectric constant of insulating material.

$$H(f) = \sum_{i=1}^{N} g_i \,.\, A(f, d_i).\, e^{-j2\pi f \tau_i} \tag{8}$$

$H(f)$ is frequency response of channel between two points. When the grid network grows big and complex it could be separated into sub-channels for individual study. A(*f*,*di*) are cable losses which could be in the form of heat or signal leakage etc. *f* is the frequency of operation, g_i is weight factor which is directly proportional to number of reflections and path followed:

$$|g_i| \leq 1 \tag{9}$$

The values of g_i and A(*f*,*di*) are determined experimentally. Based upon above given factors a mathematical model of multipath PLC is proposed in [14]:

$$H(f) = \sum_{i=1}^{N} g_i \,.\, A(f, d_i).\, e^{-j2\pi f \tau_i} \tag{10}$$

Based upon extensive investigation [14] on experimental data A(*f*,*di*) can be approximated by the mathematical formula for attenuation factor (α)

$$\alpha(f) = a_0 + a_1 . f^k \tag{11}$$

a_0 and a_1 are attenuation parameters leading to:

$$A(f,d) = e^{-\alpha(f).d} = e^{-\left(a_0 + a_1.f^k\right).d} \tag{12}$$

Using A(*f*,*di*) in $H(f)$ gives the channel model for PLC transmission line:

$$H(f) = \sum_{i=1}^{N} g_i \, . \, e^{-(a_0 + a_1.f^k).d} . \, e^{-j2\pi f\,(d_i/v_p)} \tag{13}$$

g_i = weighing factor

$e^{-(a_0 + a_1.f^k).d}$ = Attenuation portion

$e^{-j2\pi f\,(d_i/v_p)}$ = Delay portion

3.3. Existing PLC Implementations

This section gives a brief review of existing Power-Line Communication being implemented at various places and enumeration of standards involved. In Europe PLC is termed as narrow band PLC because allocated frequency band for PLC is from 3 KHz to 148 KHz, which is further divided in to four sub-bands for different applications:

- CENELEC A (35.9 Khz to 90.6 KHZ)
- CENELEC B (98.4 Khz to 121.8 KHZ)
- CENELEC C (128.1 Khz to 137.5 KHZ)
- CENELEC D (142.1 Khz to 146.8 KHZ)

Details of operation in different bands such as type of modulation, data rate, symbol size and encoding-decoding technique are enlisted in [16]. CENELEC the controlling body of PLC mechanism in Europe, follows the Stds EN 50065 (CENELEC), IEC 61000.In China PLC operates at a single Frequency band of 3 to 500 Khz. The frequency band in USA for PLC purpose is FCC band 10 kHz – 490 kHz. There is only single band with no subdivisions. Standard IEEE P1901 [17] regulating the operations of PLC, outlined two different techniques to be followed for PLC based upon modulation method to be implemented PHY layer:

- FFT OFDM: It uses Forward error correction (FEC) scheme with Convolutional Turbo Code (CTC) as underlying coding technique.
- Wavelet OFDM: It involves FEC, using concatenated Reed-Solomon (RS) and Convolutional Code, and also provides an option to add Low-density Parity Check (LDPC) to reduce errors.

3.4. PLC Channel Model Simulations, N = 4

```
clear all; clc;

%%%%%%%%%%%%% PLC multipath channel model %%%%%%%%%%%%%%

N=4; k=1; a0=0; a1=7.8e-10;

%Path parameters

g(1:N)=[0.64,0.38,-0.15,0.05];

d(1:N)=[200,222.4,244.8,267.5];

 %Spread velocity
```

```
vp=1.5e8;

ff=1:0.01:20;

f=100:2000;

    for m=1:N

  %f=1:20000;

  %f=transpose(f);

 % f0=10*f

  H(f,m)=g(m).*exp(-(a0+a1.*((ff.*1e6).^k)).*d(m)).*exp(-2i.*pi.*(ff.*1e6).*(d(m)./vp));

    end

   H0(f)=H(f,1)+H(f,2)+H(f,3)+H(f,4);

magH(f)=10*log10(abs(H0(f)));

angH(f)=angle(H(f,1)+H(f,2)+H(f,3)+H(f,4));

 subplot(2,2,1),plot(ff,magH(f))

title('N=4');xlabel('frequency in MHz'); ylabel('H(f)in dB')

grid on

subplot(2,2,2), plot(ff,angH(f))

xlabel('frequency in MHz'); ylabel('Phase')

grid on
```

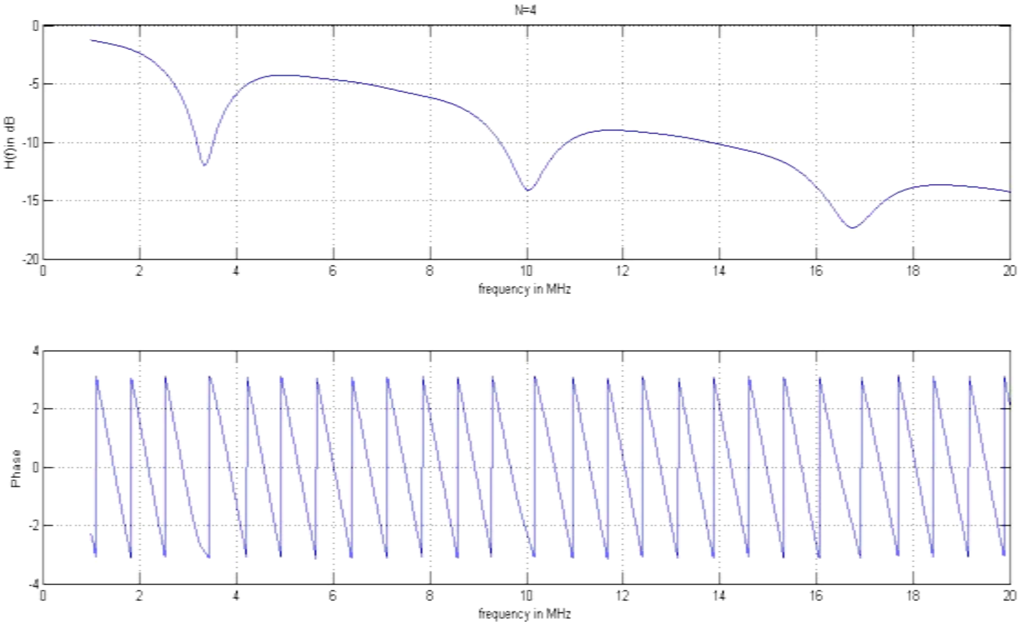

Figure 5. PLC channel model gain and phase plot, N=4

Table 1. Attenuation and path parameters for PLC channel model, N=4 [15]

<table>
<tr><td colspan="6">Attenuation Parameters</td></tr>
<tr><td colspan="2">$k = 1$</td><td colspan="2">$a_0 = 0$</td><td colspan="2">$a_1 = 7.8 * 10^{-10} s/m$</td></tr>
<tr><td colspan="6">Path Parameters</td></tr>
<tr><td>i</td><td>g_i</td><td>d_i/m</td><td>i</td><td>g_i</td><td>d_i/m</td></tr>
<tr><td>1</td><td>0.64</td><td>200</td><td>3</td><td>-0.15</td><td>244.8</td></tr>
<tr><td>2</td><td>0.38</td><td>222.4</td><td>4</td><td>0.05</td><td>267.5</td></tr>
</table>

3.5. PLC Channel Model Simulations, N = 15

```
N1= 15
g2(1:N1)=[0.029,0.043,0.103,-0.058,-0.045,-0.040,0.038,-0.038,0.071,-0.035,0.065,-0.055,0.042,-0.059,0.049];
d2(1:N1)=[90,102.4,113,143,148,200,260,322,411,490,567,740,960,110,1250];
ff=1:0.01:20;
f=100:2000;
   for m=1:N1
   H2(f,m)=g2(m).*exp(-(a0+a1.*((ff.*1e6).^k)).*d2(m)).*exp(-2i.*pi.*(ff.*1e6).*(d2(m)./vp));
   end
H02(f) = sum((H2(f,1:15))');
magH2(f)=10*log10(abs(H02(f)));
angH(f) = angle(H02(f));
subplot(2,1,1),plot(ff,magH2(f))
Title('N=15'); xlabel('frequency in MHz');ylabel('H(f)in dB')
subplot(2,1,2),plot(ff,angH(f))
xlabel('frequency in MHz');ylabel('Phase')
grid on
```

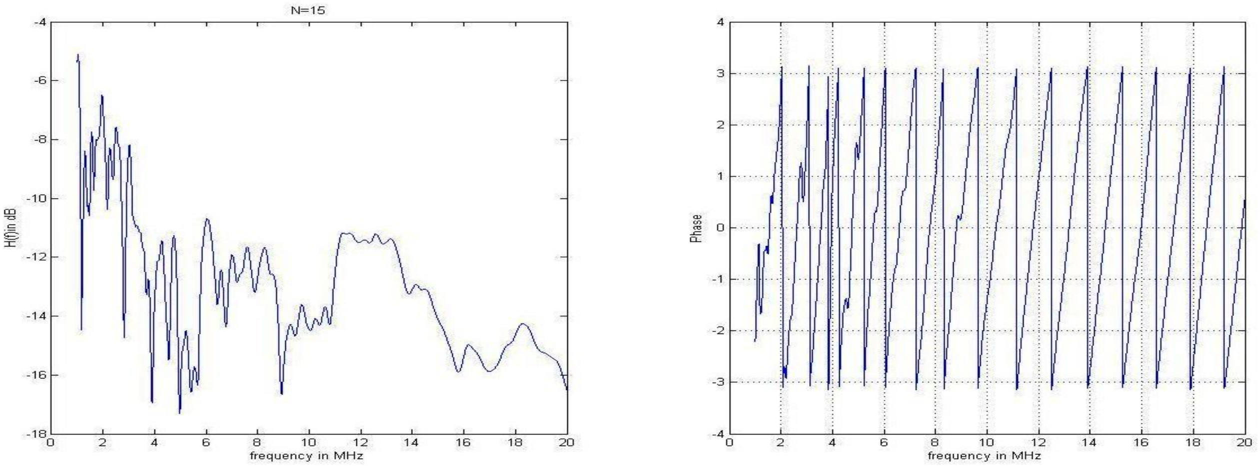

Figure 6. PLC channel model gain and phase plot, N=15

Table 2. Attenuation and path parameters for PLC channel model, N=15 [15]

Attenuation Parameters					
$k = 1$	$a_0 = 0$		$a_1 = 7.8 * 10^{-10} s/m$		
Path Parameters					
i	g_i	d_i/m	i	g_i	d_i/m
1	0.029	90	9	-0.071	411
2	0.0430	102	10	-0.035	490
3	0.0103	113	11	0.065	567
4	-0.058	143	12	-0.055	740
5	-0.045	148	13	0.042	960
6	-0.040	200	14	-0.059	1130
7	0.038	260	15	0.049	1250
8	-0.038	322			

4. BINARY PHASE SHIFT KEYING

BPSK is a subset of PSK digital modulation scheme, which uses distinct signals to represent digital symbols. In binary phase shift keying (BPSK) [18] [19], the binary symbols '1' and '0' are used to modulate the phase of the carrier.

A carrier wave can be represented as:

$$s(t) = A.\cos(2\pi f_c t) \tag{14}$$

where, A represent the peak value or amplitude of sinusoidal.

For a standard 1Ω resistor, the power dissipated is given by

$$P = \int_{-T/2}^{T/2} s(t)^2.dt \tag{15}$$

$$P = A^2/2 \tag{16}$$

$$A = \sqrt{2P} \tag{17}$$

Now, when the symbol is changed, the phase of carrier changes by 180^0.

Symbol for '1'is given by;

$$s_1(t) = \sqrt{2P}\cos(2\pi f_c t) \tag{18}$$

and symbol for '0' is given by;

$$s_2(t) = \sqrt{2P}\cos(2\pi f_c t + \pi) \tag{19}$$

$$s_2(t) = -\sqrt{2P}P\cos(2\pi f_c t) \tag{20}$$

Based on (18) and (20), BPSK signal can be represented as

$$s(t) = b(t)\sqrt{2P}\cos(2\pi f_c t) \tag{21}$$

Where, $b(t) = +1$, for binary ‘1’ and -1, for binary ‘0’

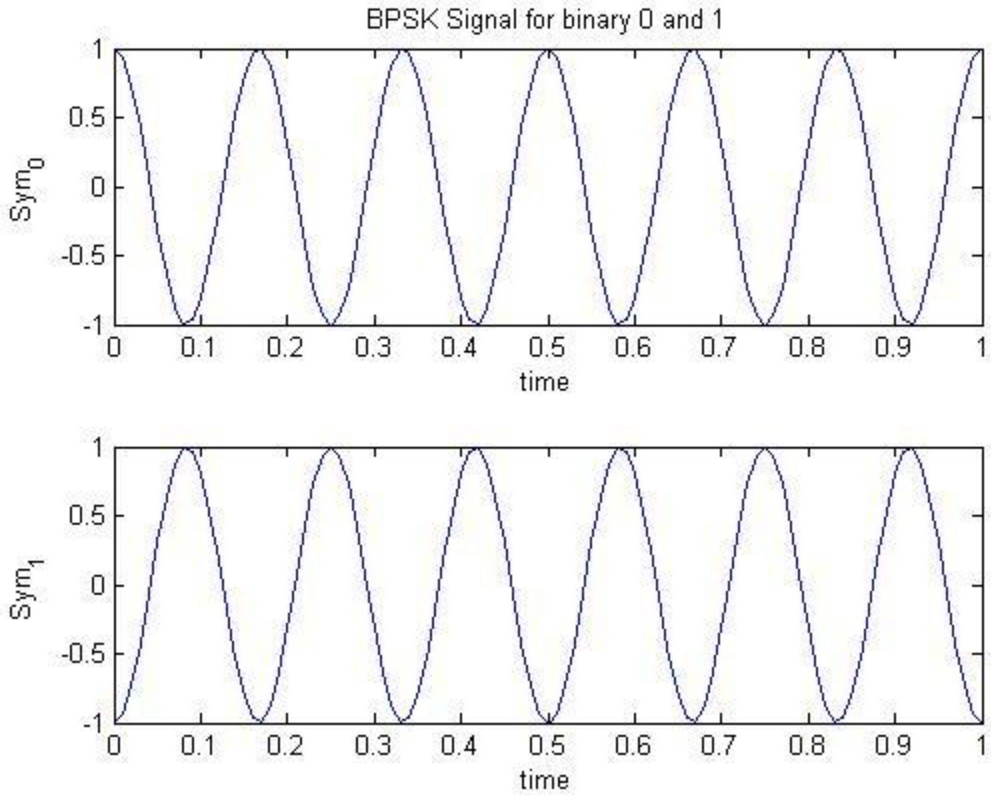

Figure 7. Sinusoidal representation of BPSK symbol ‘0’ and ‘1’

4.1. BPSK Signal Generation

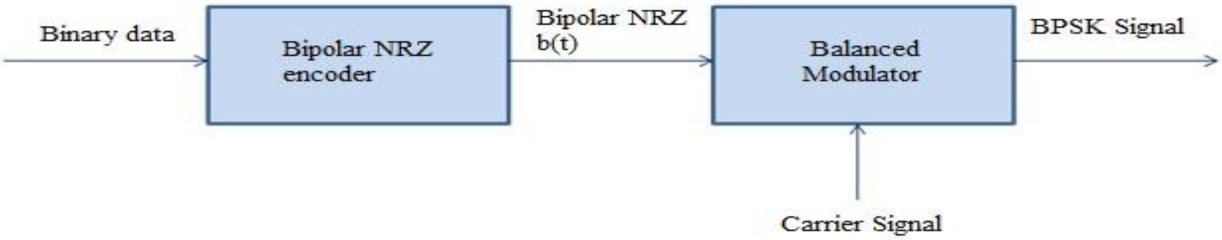

Figure 8. Block diagram for BPSK signal generation [20]

Figure 8 shows how a BPSK signal can be generated: Binary data is passed through a NRZ (Non Return to Zero) encoder; Encoded data is then modulated by mixing it with a high frequency carrier signal by a balanced modulator.

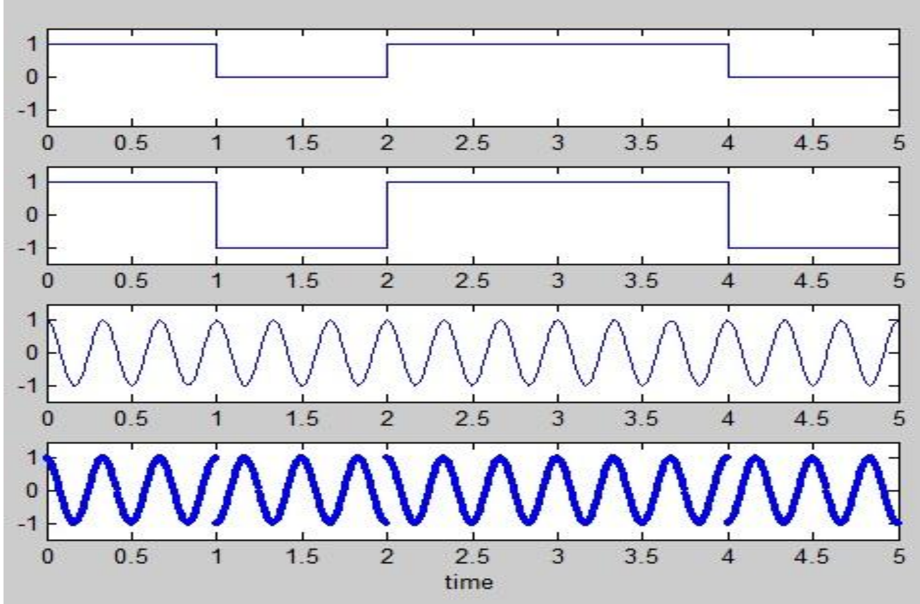

Figure 9. Waveforms representing BPSK symbols

4.2. Geometrical Representation of BPSK Signal

A BPSK signal carries information about two symbols and can be geometrically represented as follows:

$$s(t) = b(t)\sqrt{2P}\cos(2\pi f_c t) \tag{22}$$

Rearranging (22):

$$s(t) = b(t)(\sqrt{PT_b})(\sqrt{\frac{2}{T_b}}\cos(2\pi f_c t) \tag{23}$$

$$s(t) = b(t)(\sqrt{PT_b})\ \Phi 1 \tag{24}$$

Where, $\Phi 1 = \left(\sqrt{\frac{2}{T_b}}\right)\cos(2\pi f_c t)$ represent an orthogonal carrier signal.

The energy E_b it is defined in terms of power P and bit duration $T_{b:}$

$$E_b = PT_b \tag{25}$$

$$s(t) = \pm\sqrt{E_b}\ \Phi 1, \quad \text{b(t) is } \pm 1. \tag{26}$$

Geometrically, it can be represented as follows:

Figure 10. Geometric representation of BPSK

4.3. BPSK signal through PLC channel

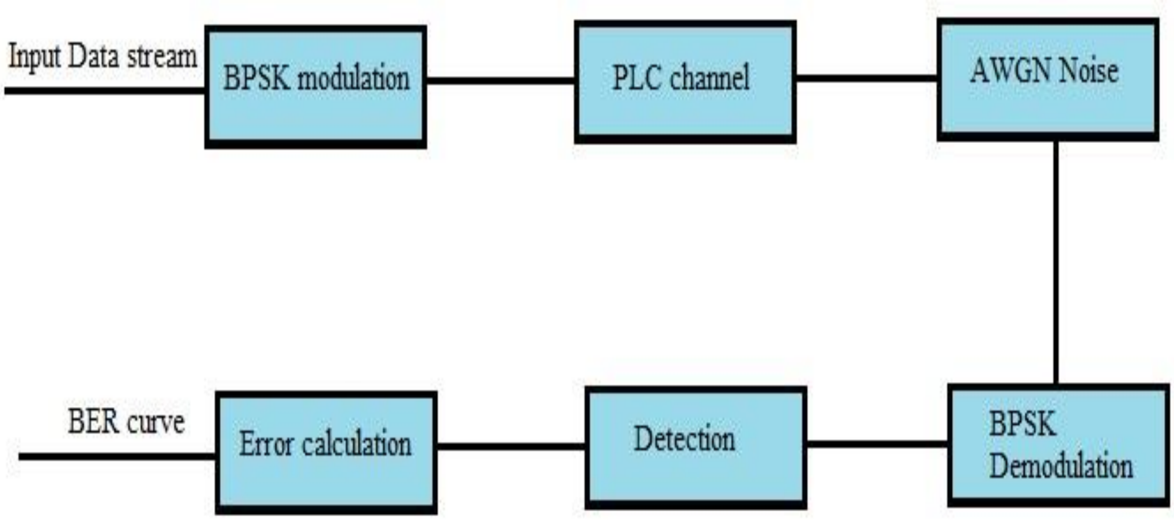

Figure 11. Block diagram of BPSK signal through PLC channel

Figure 11 explains the process of passing BPSK signal through PLC channel. This would help to evaluate the throughput and BER curves. First, input data stream BPSK modulated and converted into a stream of +1 and 0s. This modulated data stream is further passed through PLC channel, which degraded the signal. AWGN is then added to data stream coming from PLC channel. At the receiver end BPSK signal is demodulated and then detected for +1 and 0s. This detected stream of +1 and 0s is then compared with input data stream and number of errors are detected to form BER curves.

5. INTRODUCTION TO OFDM

Orthogonal Frequency division multiplexing, OFDM [20] due to its flexibility and computational efficiency, is one of the most promising techniques available. It involves a combination of both modulation and multiplexing. As discussed in the previous section:

- Modulation is a change in the parameters (frequency, phase and amplitude) of the carrier signal according to the message signal.
- Multiplexing is the method of sending multiple signals on the same channel; also maintaining their integrity at the receiver end.

OFDM converts a given high-bit-rate data stream into several parallel lower-bit-rate streams and modulates each stream on separate carriers, often called subcarriers, or tones. It is an extension or a special case of FDM (Frequency Division Multiplexing), in which a given bandwidth is divided into narrow channels to send multiple data streams at the same time. Here total bandwidth (*BW*) is divided in to ‘n’ (n=5) channels.

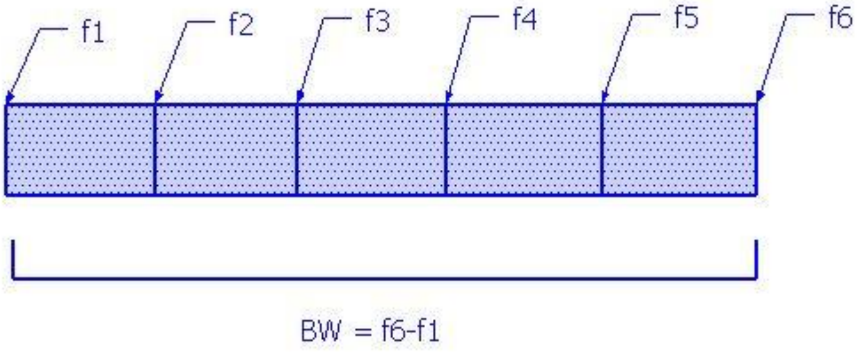

Figure 12. FDM concept of frequency division

Bandwidth of each channel is total BW divided by number of channels.

$$f2 - f1 = BW/\mathrm{n} \tag{27}$$

In FDM neighboring channels interfere with each other hence require guard bands to separate them. Introduction of guard bands reduces the individual sub-channel bandwidth.

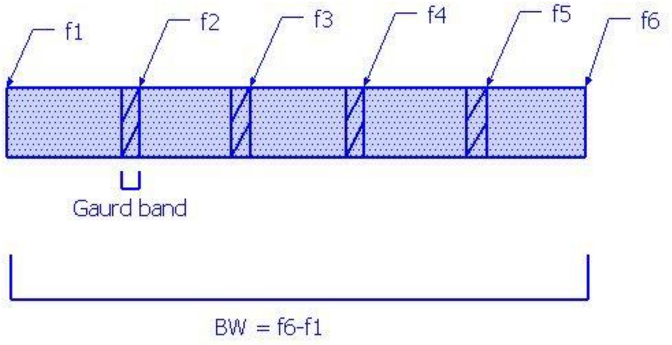

Figure 13. FDM with guard bands

Bandwidth of n$^{\mathrm{th}}$ channel = $f2 - f1 - \text{Gaurd Bandwidth}$

OFDM introduces the concept of orthogonality of sub carriers. Orthogonal subcarriers rule out the possibility of inter-channel interference. In order to be orthogonal, two signals must be uncorrelated over symbol duration time.

$$\int_0^T S1(t).S2(t).dt = 0 \tag{28}$$

5.1. OFDM Block Diagram

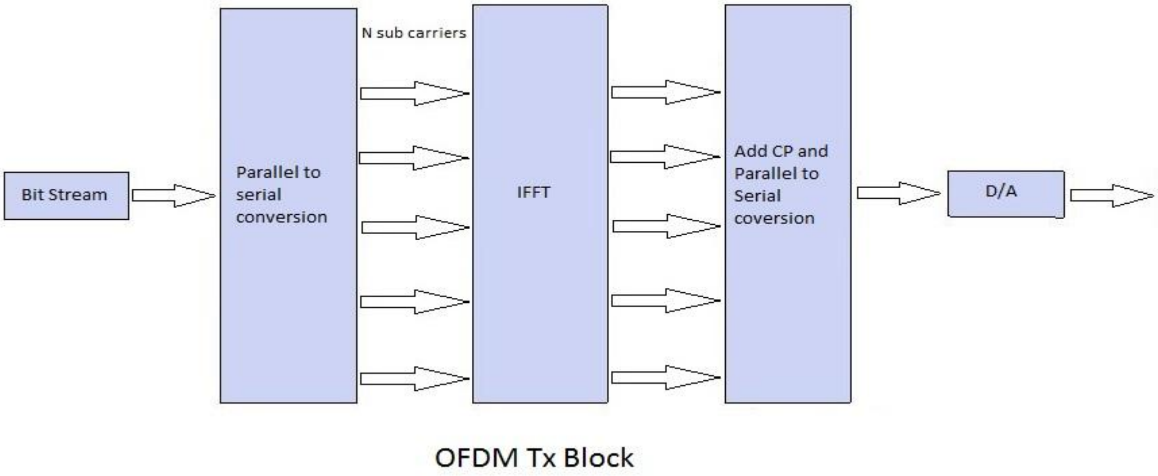

Figure 14. OFDM Transmission block

A serial bit stream when equally distributed among parallel subcarriers decreases the bit rate per channel, which allows symbol time to be large enough for multicarrier modulation schemes to eliminate or at least minimize inter-symbol interference (ISI). Increasing the symbol duration induces channel delays, which are very insignificant compared to the symbol duration as a whole. Therefore, in high-data-rate systems in which the symbol duration is small, being inversely proportional to the data rate, splitting the data stream into many parallel streams increases the symbol duration of each stream such that the delay spread is only a small fraction of the symbol duration. Example:

```
X[N] = randsrc(1,20,[1,-1])

X[N] = [1  1  -1  1  1  1  -1  -1  1  -1  1 -1  1  1  1 -1 -1  1  1 -1]

N=length(X);
```

```
Sub_carrier=reshape (x,4,5)
```

$$\text{Sub\_Carrier(1:4)} = \begin{bmatrix} 1 & 1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 \\ 1 & -1 & 1 & 1 & 1 \\ -1 & -1 & 1 & 1 & -1 \end{bmatrix}$$

Modulation followed by serial to parallel conversion generates frequency components, which are converted to time samples using Inverse Fast Fourier Transform (IFFT). The OFDM symbol is generated after IFFT, which is given by:

$$x[n] = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i]\, e^{2\pi ni/N}, \quad 0 \le n \le N-1 \tag{29}$$

Each x[n] represents a sum of modulated symbols with frequency modulated by $e^{2\pi ni/N}$ factor.

5.2. CP (Cyclic Prefix)

The multipath environment degrades the baseband signal, due to constructive and destructive addition of delayed signals. The process of delayed symbols distorting each other is known as ISI (Inter Symbol Interference). In OFDM this problem is tackled by the addition of CP to the symbol. After modulation, CP (Cyclic prefix) is added at the end of every symbol. CP serves the same purpose as guard bands in frequency division multiplexing. Addition of CP increases the symbol duration and eventually reduces the symbol rate across the channel. ISI (Inter Symbol Interference) is reduced on introduction of CP.

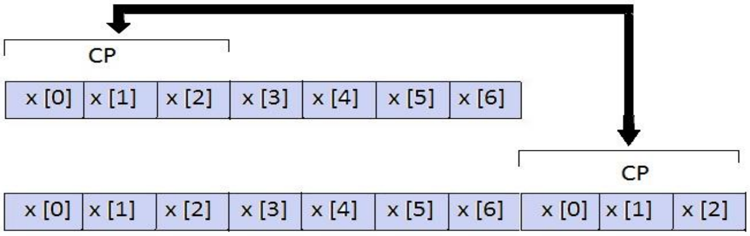

Figure 15. Concept of CP in OFDM symbol

Let, X[0] be the OFDM symbol of length N

X[0] = x[0], x[1], x[2], x[3]….. x[N-1]

OFDM symbol with addition of CP

X = x[N-L+1], x[N-L+2] …… x[N-2], x[N-1],x[0], x[1], x[2], x[3]….. x[N-1]

Symbol length = N+L+1, length of Cyclic prefix is decided based upon the channel delay. After the addition of CP to the symbols, they are passed through the parallel to serial converter. OFDM symbol preceding CP make convolution between channel and OFDM symbol, circular in nature.

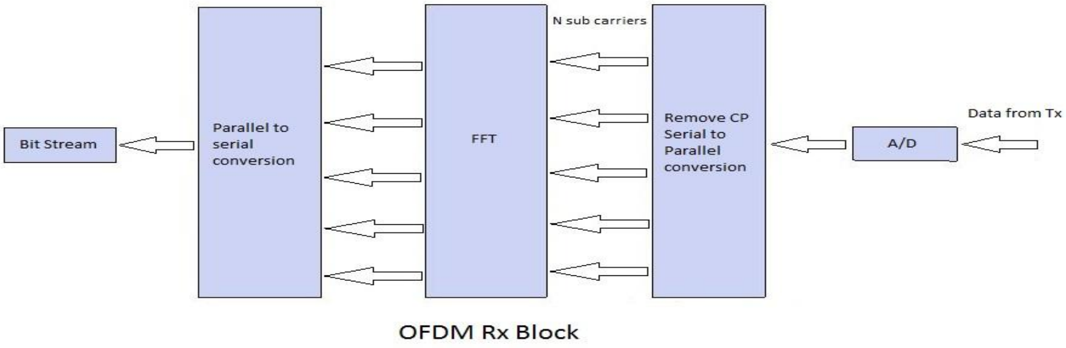

Figure 16. OFDM Receiver block

6. SIMULATION RESULTS

Following steps have been used:

1. Random bits generated are modulated to BPSK signal
2. Out of the 64 total number of subcarriers only 52 are occupied, over which data is transmitted. The rest of the 14 subcarriers remain empty. Modulated BPSK symbols are assigned to 52 subcarriers from -26 to -1 and +1 to +26. Unoccupied subcarriers are padded with zeros. It is at this step where serial to parallel conversion takes place.
3. IFFT is performed to generate OFDM signal, and CP (Cyclic Prefix) is added to reduce Inter Symbol Interference.

   Length of CP should be no less than the delay spread of PLC channel.

```
%%%%%%%% Length of CP %%%%%%%%%%%%

vp  =   1.5e8;

di  =   [200,222.4,244.8,267.5];

davg = mean(di);

tau =davg/vp;

L_CP = ceil(tau*20e6);

L_CP = 32;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Length of CP =32

Total length of OFDM symbol = 64+32= 96

4. PLC channel model is generated

$$H(f) = \sum_{i=1}^{N} g_i \, . \, e^{-(a_0 + a_1 . f^k).d} . \, e^{-j2\pi f\,(d_i/v_p)} \tag{30}$$

5. Every OFDM symbol is convolved with the PLC channel generated.
6. AWGN, Gaussian noise of unit variance and zero mean is generated and added to OFDM symbols passed through the PLC channel.
7. Parallel data stream is reshaped into serial vector and CP is removed.
8. Serial data received is converted to frequency domain and divided by the frequency domain of the PLC channel in order to equalize the data. Data is extracted from occupied subcarriers.
9. Received bit stream is detected for BPSK signals. Hard decision making is preformed.
10. Transmitted and received data streams of BPSK symbols are compared to each other and the numbers of errors are calculated.
11. Montecarlo simulation model is followed and the whole process is repeated multiple time to generate BER curves. Table 3 lists the parameter specifications used in simulation model.

Table 3. Parameters used in simulation model for generating BER curves.

Simulation Model	Monte Carlo
Number of subcarriers	64
FFT block size	128
Number of occupied sub carriers	52
Length of CP	32
Number of bits	52x10^6
Number of runs	40

6.1. BER Vs SNR Curve Generated

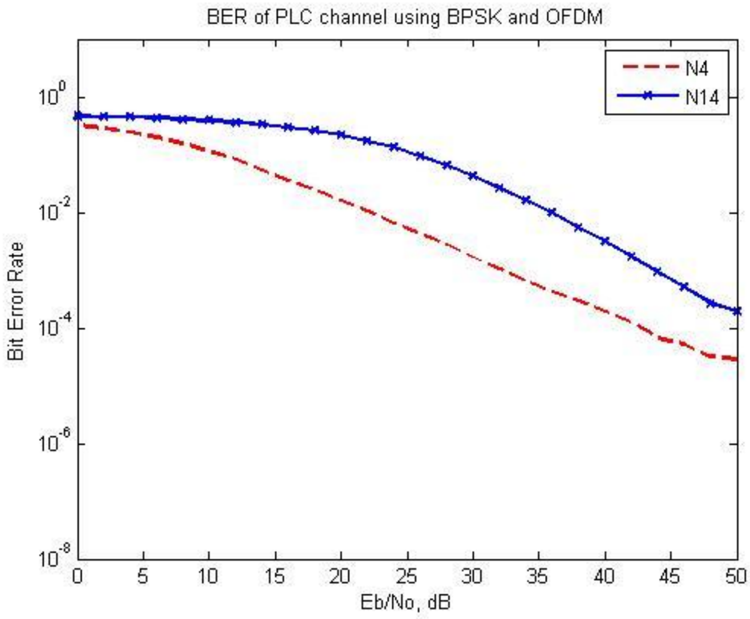

Figure 17. BER curve for PLC channel, N=4 and N=14

7. CONCLUSION

This paper provides the review of Smart Grid and its emergence from existing power grid while enlisting some of its advantages and forth coming challenges. Certain industry standards claim promising data throughputs over last mile of power line communication. Homeplug Powerline Alliance Standards is one of leading group which specializes in home PLC products and services [25]. Home plug releases series of standards named Homeplug 1.0, turbo, AV, offering physical layer data throughput of 14, 85 and 200 Mbps respectively within a home network. . Comparing to MoCA technology over coaxial cables with data throughput upto 270 Mbps and Ethernet (Cat 5 UTP) maxing up to 1 Gbps, PLC does not fare well [26]. Following are some major problems which need to be addressed:

- Analytical Modeling
- Reliability (failure reduction)
- Multipath Propagation (delay)
- Problem identification (fault detection)
- Security (unauthorized access to propagation and devices on network)
- Interference (with other operations working at same the frequency range)
- Bandwidth (to accommodate high data rate demanding services like voice and video communication)

Most of the existing work could be separated into two categories:

- Experimental
- Analytical

Experimental setup could be constrained to the level of lab for generating impulsive noise [22][23][24] and study its characteristics with different modulation techniques in real time. Another major outcome is the study of multipath propagation under different techniques and environment. These setups have given mathematical models for noise involved and PLC transmission channel. Based upon these models most of the analytic work is done by simulating for various different approaches involved. Most of the analytic work is performance evaluation of combination of different modulation techniques like BPSK,8PSK,QAM +FFT, cosine, Wavelet transform +OFDM,COFDM +Error detection code (CRC, RS code, CTC, ARQ, parity check) +different receiver structures. These combinations try to addresses one or more issues enumerated under major problems. With most of the information discussed briefly in this review paper MATLAB simulations could be done and different results can be compared.

8. REFERENCES

[1] J. W. Bialek, "Why Has it Happened Again? Comparison Between the UCTE Blackout in 2006 and The Blackouts of 2003," *IEEE Lausanne Power Tech, 2007*, pp. 51-56, July, 2007.

[2] S. T. Mak, "Knowledge Based Architecture Serving as a Rigid Framework for Smart Grid Applications," *Innovative Smart Grid Technologies (ISGT),* pp. 1-8, Jan, 2010.

[3] J. Taneja, R. Katz, D. Culler, "Defining CPS Challenges in a Sustainable Electricity Grid," *Int. Conference Cyber-Physical Systems (ICCPS),* pp.119-128, April, 2012.

[4] D. Rua, D. Issicaba, F. J. Soares, P. M. R. Almeida, R. J. Rei and J. A. P. Lopes, "Advanced Metering Infrastructure Functionalities for Electric Mobility," *Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, pp. 1-7, Oct, 2010.

[5] A. Moreno-Munoz and J. J. G De La Rosa, "Integrating Power Quality to Automated meter Reading," *IEEE Ind. Electron. Mag.*, vol.2, pp. 10-18, June, 2008.

[6] S. Ritter, H. Ruttinger, S. Ritter, P. Bretschneider and D. Westermann, "New Approaches for Smart Grid Requirements: Grid Protection and Optimization of Distribution Grid Operation," *IEEE Power and Energy Society General Meeting*, pp. 1-7, July, 2011.

[7] K. Sedghisigarchi, "Residential Solar Systems: Technology, Net-metering, and Financial Payback," *Elect. Power & Energy Conference (EPEC),* pp. 1-6, Oct, 2009.

[8] A. Aggarwal, S. Kunta and P. K. Verma, "A Proposed Communications Infrastructure for the Smart Grid," *Innovative Smart Grid Technologies (ISGT),* pp.1-5, Jan, 2010.

[9] M. Gotz and K. Dostert, "A Universal High Speed Powerline Channel Emulation System," *Int. Zurich Seminar Broadband Commun., Access, Transmission, Networkin,.* pp.24.1-24.6, 2002.

[10] J. Bausch, T. Kistner, M. Babic and K. Dostert, "Characteristics of Indoor Power Line Channels in the Frequency Range 50-500 khz," *Proc. IEEE Int. Symp. on Power Line Commun. and its Applications, 2006.*

[11] M. Bauer, W. Plappert, W. Chong and K. Dostert, "Packet-oriented Communication Protocols for Smart Grid Services Over Low-speed PLC," *IEEE ISPLC,* pp. 89-94, April, 2009.

[12] H. Meng, Y.Ll. Guan and S. Chen, "Modeling and Analysis of Noise Effects on Broadband Power-line Communications," *IEEE Trans. Power Delivery*, vol.20, pp. 630- 637, April, 2005.

[13] M. Zimmermann and K. Dostert, "Analysis and Modeling of Impulsive Noise in Broadband Powerline Communications," *EEE Trans. Elecfromugn. Compat.*, vol. 44, pp. 249-258, 2002.

[14] Y. H. Ma, P. L. So, E. Gunawan and Y. L. Guan, "Analysis of Impulsive Noise and Multipath Efects on Broadband Power Line Communcations" *Int. conf. Power System Technology-POWERCON*, Nov, 2004.

[15] M. Zimmermann and K. Dostert, "A Multipath Model for the Powerline Channel," *IEEE Trans.Commun.,* vol.50, pp. 553-559, April, 2002.

[16] Supplement to PLC G3 physical layer specification for operation in CENELEC B/C/BC/D/BCD/BD frequency bands.

[17] Y. P. Jae, S. H. Choong, L. Sungwon, "An efficient MAC scheme with modified RTS/CTS of IEEE P1901," *Int. Conference Information Networking (ICOIN),* pp. 230-234, Jan, 2011.

[18] A. B. Carlson, P. B. Crilly and J. C. Rutledge, “Communication Systems, An Introduction to Signals and Noise in Electrical Communications”, *McGraw Hill,* 2002, pp. 618-620.

[19] B. Sklar, “Digital Communications, Fundamental and Applications”, *Prentice Hall P T R,* 2001, pp. 173-174.

[20] J. S. Chitode, “Principles of Communication”, *Tech. Publications*, Pune, India, pp. 6.5-6.14, 2008.

[21] A. Goldsmith, “Wireless Communication” *Cambridge University Press*, 2009. pp. 359-362.

[22] R. M. Rodriguez-Osorio, L. D. H. Ariet, A. D. C. Urbina and M. C. Ramon , "A DSP-Based Impulsive Noise Generator for Test Applications," *IEEE Trans. Ind. Electron.,*vol.54, pp. 3397-3401, Dec, 2007.

[23] M. Tlich, H. Chaouche, A. Zeddam and P. Pagani, "Novel Approach for PLC Impulsive Noise Modelling," *IEEE Int. Symp. Power Line Commun. and Its Applications*, pp. 20-25, April, 2009.

[24] M. Katayama, T. Yamazato and H. Okada, "A Mathematical Model of Noise in Narrowband Power Line Communication Systems," *IEEE J. Selected Areas in Commun.*, vol.24, pp. 1267-1276, July, 2006.

[25] M. Yan,Y. Gao, G. Qin and L. Kang, "Research and Design on MAC Architecture of Digital Home Network," *IFCSTA Int. Forum Comput. Sci.-Technology and Applications*, vol.2, pp.203-206, Dec, 2009.

[26] M. S. Yousuf, S. Z. Rizvi and M. El-Shafei, "Power Line Communications: An Overview - Part II," *ICTTA Int. Conference Inform. and Commun. Technologies: From Theory to Applications,* pp.1-6, April, 2008.