# Performance Analysis of an OFDM Broadband Power Line Communication (BPLC) System with Multiple Receiving Antennas

By

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The thesis titled **“Performance Analysis of an OFDM Broadband Power Line Communication (BPLC) System with Multiple Receiving Antennas”** submitted by Md. Muhaimin, Student No:100706102P, Session: October, 2007, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING on February 25, 2014

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# DEDICATION

*To my parents and wife.*

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# ABSTRACT

Power line networks are an excellent infrastructure for broadband communication, though there exists some technical difficulties as noise, attenuation, multipath scenario etc. are presented in power line system as power lines are not specifically designed for data communication purposes. In this thesis, analytical approach is presented for a broadband power line communication system (BPLC) to evaluate the bit error rate (BER) with different channel models e.g. 4-path model, 15-path model and 5-path model. A broadband power line system is considered using orthogonal FDM (OFDM) modulation and analysis is carried out to find the expression of the signal to noise ratio at the output of a power line communications system with OFDM modulation and demodulation taking into considerations the effect of channel impairments using the three different channel models with single OFDM receiver. Further, analysis is extended to multiple OFDM receivers for the PLC system using space diversity in receiving end.

Results are evaluated for different number of OFDM subcarriers and different channel parameters with single receiver and multiple receiver PLC systems. Results are evaluated for a bandwidth of 20 MHz using the channel coefficients for the different path models. It is found that there are significant improvements in BER performance with increase in the number of OFDM subcarrier for a given system bandwidth of 20 MHz. Further it is noticed that there is significant improvement in receiver sensitivity with increase in number of receiver at a given value of OFDM subcarrier N for a particular BER. Finally, the comparison between the power line channel models depicts that 4-path model provides better estimates of channel performance compared to 15-path model and 5-path model.

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| | |
|---|---|
| $\gamma$ | Propagation Constant |
| $g_i$ | Weighting Factor of ith path |
| $\tau_i$ | Delay of ith path |
| $\varepsilon_r$ | Dielectric Constant of the Insulating Material |
| $c_0$ | Speed of Light |
| $d_i$ | Length of the ith Cable |
| $v_p$ | Propagation Speed |
| $P$ | Number of Multipaths |
| $a_0, a_1$ | Attenuation Parameters |
| $\sigma_g^2$ | Background Noise Power |
| $\sigma_i^2$ | Impulsive Noise Power |
| $R_{nb}$ | Power Spectral Density of Coloured Background Noise |
| $\mu_z$ | Mean of Middleton Class A noise model |
| $\sigma_m^2$ | Variance of Middleton Class A noise model |
| $E_b$ | Energy of the Signal |
| $N_0$ | Noise Spectral Density |
| $h$ | Channel Impulse Response |
| $H_k$ | Sub-channel Response |
| $T_b$ | Bit Rate |
| $N$ | Number of OFDM Subcarriers |
| $T_N$ | Information Time of OFDM Signal |
| $T_{guard}$ | Guard Time of OFDM Signal |
| $\alpha_g$ | Guard Interval Ratio |
| $P_b$ | Average Probability of Error |
| $L$ | Number of Receiving Antennas |
| $\Gamma_c$ | Average SNR per bit in each Diversity Channel |

# List of Abbreviations

| | |
|---|---|
| BPLC | Broadband Power Line Communications |
| DTE | Data Terminal Equipment |
| PLC | Power Line Communications |
| PLT | Power Line Telecommunications |
| PPC | Power Plus Communications |
| BPS | Bits Per Second |
| EMC | Electromagnetic Compatibility |
| LAN | Local Area Network |
| PSD | Power Spectral Density |
| SC | Single Carrier |
| MC | Multi-Carrier |
| ISI | Inter Symbol Interference |
| OFDM | Orthogonal Frequency Division Multiplexing |
| DMT | Discrete Multi-Tone |
| FEQ | Frequency Equalizer |
| PAR | Peak-to-Average Ratio |
| BPSK | Binary Phase Shift Keying |
| FM | Frequency Modulation |
| SNR | Signal to Noise Ratio |
| ICI | Inter Channel Interference |
| FFT | Fast Fourier Transform |
| RF | Radio Frequency |
| CDMA | Code Division Multiple Access |
| QoS | Quality of Service |
| TDMA | Time Division Multiple Access |
| CA | Collision Avoidance |

| | |
|---|---|
| MAI | Multiple Access Interference |
| FDMA | Frequency Division Multiple Access |
| TDD | Time Division Duplexing |
| FDD | Frequency Division Duplexing |
| ADC | Analog to Digital Converter |
| WLAN | Wireless Local Area Network |
| MIMO | Multiple Input and Multiple Output |
| STC | Space Time Coding |
| EGC | Equal Gain Combining |
| MRC | Maximal-ratio combining |
| AWGN | Additive White Gaussian Noise |
| BER | Bit Error Rate |
| SINR | Signal to Interference plus Noise Ratio |
| DFT | Discrete Fourier Transform |
| MTL | Multi-conductor Transmission Line |
| PVC | Poly vinyl Chloride |
| IAT | Inter Arrival Time |
| WGN | White Gaussian Noise |
| PDF | Probability Density Function |
| IDFT | Inverse Discrete Fourier Transform |
| QAM | Quadrature Amplitude Modulation |
| PSK | Phase Shift Keying |

# Chapter 1

# Introduction

## 1.1 Introduction to Power Line Communication System

Communication is the field of study concerned with the transmission of information through various means. It can also be defined as technology employed in transmitting messages or the content of data (speech, signals, pulses etc.) from one node to another. Electrical communication systems are designed to send message or information from a generating source to one or more destinations. The information generated from the source may be of the form of voice images or plain text. A transducer is usually required to convert the output of a source into an electrical signal that is suitable for transmission. At the destination, a similar transducer is also required to convert the electrical signals that are received into a form that is suitable for the user, The exchange of thoughts , messages or information, as by speech, signals, writing or behavior is known as communication. Any transmission, emission or reception of signal by wire, radio, visual, optical or other electromagnetic systems are known as electrical communication. In telecommunication, a communications system is a collection of individual communications networks, transmission systems, relay stations, tributary stations, and data terminal equipment (DTE) usually capable of interconnection and interoperation to form an integrated whole. The heart of the communication system consists of three basic parts, namely the transmitter, the channel and the receiver [1].

"*Power Line Communications*" basically means any technology that enables data transfer at narrow or broad band speeds through power lines by using advanced modulation technology. This can be done by adding a modulated carrier signal to the wiring system [5].

Depending on the country, the institution and the company, power line communications are grouped under several different key words:

- **PLC** (*Power Line Communications*)
- **PLT** (*Power Line Telecommunications*)
- **PPC** (*Power Plus Communications*)

Power line communication has been around for quite some time, but has only been used for narrow band tele-remote relay applications, public lighting and home automation.

Broadband over PLC only began at the end of the 1990s:

- **1950**: at a frequency of 10 Hz, 10 kW of power, one-way: town lighting, relay remote control.
- **Mid 1980s**: beginning of research into the use of the electrical grid to support data transmission, on bands between 5 – 500 kHz, always in a one-way direction,
- **1997**: first tests for bidirectional data signal transmission over the electrical supply network and the beginning of research by Ascom (Switzerland) and Norweb (U.K.)
- **2000**: first tests carried out in France by EDF R&D and Ascom.

The general electrical supply systems consist of three network levels that can be used as a transmission medium for the realization of PLC networks:

- High-voltage (110–380 kV) networks connect the power stations with large supply regions or big customers. They usually span very long distances, allowing power exchange within a continent. High-voltage networks are usually realized with overhead supply cables.
- Medium-voltage (MV) (10–30 kV) networks supply larger areas, cities and big industrial or commercial customers. Spanned distances are significantly shorter than in the high-voltage networks. The medium-voltage networks are realized as both overhead and underground networks.
- Low-voltage (230/400 V, in the USA 110 V) networks supply the end users either as individual customers or as single users of a bigger customer. Their length is usually up to a few hundred meters. In urban areas, low-voltage networks are

realized with underground cables, whereas in rural areas they exist usually as overhead networks.

In-home electrical installations belong to the low-voltage network level. However, internal installations are usually owned by the users. They are connected to the supply network over a meter unit (M). On the other hand, the rest of the low-voltage network (outdoor) belongs to the electrical supply utilities.

Low-voltage supply networks directly connect the end customers in a very large number of households worldwide. Therefore, the application of PLC technology in low-voltage networks seems to have a perspective regarding the number of connected customers. On the other hand, low-voltage networks cover the last few hundreds of meters between the customers and the transformer unit and offer an alternative solution using PLC technology for the realization of the so-called “last mile” in the telecommunications access area.

### 1.2 Operating principles of PLC

PLC Broadband technology is capable of transmitting data via the electrical supply network, and therefore can extend an existing local area network or share an existing internet connection through electric plugs with the installation of specific units.

The principle of PLC consists in superimposing a high frequency signal (1.6 to 30 Mhz) at low energy levels over the 50 Hz electrical signal. This second signal is transmitted via the power infrastructure and can be received and decoded remotely. Thus the PLC signal is received by any PLC receiver located on the same electrical network.

An integrated coupler at the PLC receiver entry points eliminates low frequency components before the signal is treated [6].

### 1.2.1 Narrowband PLC:

The narrowband PLC networks operate within the frequency range specified by the CENELEC norm (Tab. 1.1). This frequency range is divided into three bands: A, to be used by power supply utilities, and B and C, which are provided for private usage. The utilities use narrowband PLC for the realization of the so-called energy-related services. Frequency bands B and C are mainly used for the realization of building and home automation. Nowadays, the narrowband PLC systems provide data rates up to a few thousand bits per second (bps). The maximum distance between two PLC modems can be up to 1 km. The narrowband PLC systems apply both narrowband and broadband modulation schemes.

A very important area for the application of narrowband PLC is building/home automation. Also a power utility can use PLC to realize internal communications between its control center and different devices, ensuring remote control functions, without building extra telecommunications network or buying network resources at a network provider (Fig. 1.4). Simultaneously, PLC can be used for remote reading of a customer's meter units, which additionally saves cost on the personnel needed for manual meter reading. Finally, PLC can also be used by the utilities for dynamic pricing (e.g. depending on the day time, total energy offer, etc.), as well as for observation and control of energy consumption and production.

### 1.2.2 Broadband PLC:

Broadband PLC systems provide significantly higher data rates (more than 2 Mbps) than narrowband PLC systems. Where the narrowband networks can realize only a small number of voice channels and data transmission with very low bit rates, broadband PLC networks offer the realization of more sophisticated telecommunication services; multiple voice connections, high-speed data transmission, transfer of video signals, and narrowband services as well. Therefore, PLC broadband systems are also considered a capable telecommunications technology.

The realization of broadband communications services over powerline grids offers a great opportunity for cost-effective telecommunications networks without the laying of new cables. However, electrical supply networks are not designed for information transfer and there are some limiting factors in the application of broadband PLC technology. Therefore, the distances that can be covered, as well as the data rates that can be realized by PLC systems, are limited. A further very important aspect for application of broadband PLC is its Electromagnetic Compatibility (EMC) [1].

### 1.3 Applications of Power Line Communication

There has been an increasing interest to utilize the power line infrastructure for broadcast communication services and several field trials are presently being carried out throughout the world [7]. The advantage of Power Line Communications (PLC) is very obvious because of the availability of power lines and power outlets. The potential of power lines to deliver the broadband services, such as fast Internet access, telephone and fax services, and home networking is an emerging new technology in telecommunications industry [8-11].

Moreover, access to the internet is as essential as access to electrical power. Since devices that access the Internet are normally plugged into an electrical outlet the unification of these two networks seems a compelling option. There is also growing interest in the prospects of re-using in-building Power Line cables to provide a broadband Local Area Network within the home or office. The major advantage offered by PL-based home-networks is the availability of an existing infrastructure of wires and wall outlets so that frequent revision or new cable installation is averted [12-13].

Besides the traditional access and home-LAN applications, PLCs also have other interesting applications. Today in the construction of vehicles, ranging from automobile to ships, from aircraft to space vehicles [14], separate cabling is used to establish the underlying physical layer of a local command and control network. As LAN technology and associated networking protocols continue to advance, local command and control networks will evolve toward broadband local networks, supporting a large number of sophisticated devices and software based applications.

### 1.4 PLC Standards:

The communications over the electrical power supply networks is specified in a European standard CENELEC EN 50065, providing a frequency spectrum from 9 to 140 kHz for powerline communications (Tab. 1.1). CENELEC norm significantly differs from American and Japanese standards, which specify a frequency range up to 500 kHz for the application of PLC services.

**Table 1.1: CENELEC bands for powerline communications**

| Band | Frequency Range (kHz) | Max. Transmission Amplitude (V) | User Dedication |
|---|---|---|---|
| A | 9-95 | 10 | Utilities |
| B | 95-125 | 1.2 | Home |
| C | 125-140 | 1.2 | Home |

CENELEC norm makes possible data rates up to several thousand bits per second, which are sufficient only for some metering functions (load management for an electrical network, remote meter reading, etc.), data transmission with very low bit rates and the realization of few numbers of transmission channels for voice connections. However, for application in modern telecommunications networks, PLC systems have to provide much higher data rates (beyond 2Mbps). Only in this case, PLC networks are able to compete with other communications technologies, especially in the access area.

For the realization of the higher data rates, PLC transmission systems have to operate in a wider frequency spectrum (up to 30 MHz). However, there are no PLC standards that specify the operation of PLC systems out of the frequency bands defined by the CENELEC norm. Currently, there are several bodies that try to lead the way for standardization of broadband PLC networks, such as the following:

- PLCforum [PLCforum] is an international organization with the aim to unify and represent the interests of players engaged in PLC from all over the world. There are more than 50 members in the PLCforum; manufacturer companies, electrical supply utilities, network providers, research organizations, and so on. PLCforum is organized into four working groups: Technology, Regulatory, Marketing and Inhouse working group.
- The HomePlug Powerline Alliance [HomePlug] is a not-for-profit corporation formed to provide a forum for the creation of open specifications for high-speed home powerline networking products and services. HomePlug is concentrated on in-home PLC solutions and it works close to PLCforum as well.

Standardization activities for broadband PLC technology are also included in the work of European Telecommunications Standards Institute (ETSI) and CENELEC.

## 1.5 Limitations of Power Line Communication

There are some challenges for communication over power line such as noise, attenuation and multipath propagation which exist due to stochastic changes in the network load impedances, branches etc.

### 1.5.1 Multipath Propagation in Power Line Communication

In any given power line channel (medium voltage or low voltage or indoor), the number of interconnected branches in the link between sending and receiving ends, different terminal loads and branch lengths cause multipath (due to transmission and reflection of signals between the transmission line segments) characteristics that are similar to wireless channel. This multipath causes degradation of the signals propagating in the link between the sending and receiving ends [15].

### 1.5.2 Attenuation in Power Line Communication

The attenuation of powerline links is mainly influenced by cable losses and multipath fading due to reflections at branching points so that every link has its own attenuation profile. However, there are significant similarities regarding links with similar length, layout, and cable types [10].

*Short-Distance Link:* Short distance links (100–200 m) with only a few branches (1 to 4) mostly exhibit typical attenuation values starting from a few decibels at 500 kHz going up to 40–70 dB at 20 MHz.

*Long-Distance Link:* Typical long-distance links 300 m with PVC-insulated underground cables exhibit much higher attenuation, mainly caused by higher losses due to length and many branches (up to 15). Moreover, attenuation is often intensified by deep notches caused by multipath fading. Attenuation typically starts in a range from 10 to 30 dB at 500 kHz and may reach values of more than 80 dB at frequencies of 5–8 MHz (which is close to the noise floor of the used measuring equipment).

*Length Profile:* Since positions and depths of notches do not depend on the length of the link, but only on properties of the branches (length and mismatch), it is logical not to consider the impact of notches when specifying a length profile including only basic attenuation characteristics.

### 1.5.3 Noise in Power Line Communication

Besides signal distortion, due to cable losses and multi-path propagation, noise is the most crucial factor influencing digital communications over powerline networks. Opposite to many other communication channels the powerline channel does not represent an additive white Gaussian noise (AWGN) environment.

Extending the basic classification provided by [16] for the frequency range below 100 kHz, the additive noise in broadband powerline communication channels can be separated into five classes:

(i) **Colored background noise:** Colored background noise has a relatively low power spectral density (PSD), varying with frequency. This type of noise is mainly caused by summation of numerous noise sources with low power. Its PSD varies over time in terms of minutes or even hours.

(ii) **Narrow band noise:** Narrow band noise is mostly sinusoidal signals, with modulated amplitudes. This type of noise is mainly caused by ingress of broadcast stations in the medium and short wave broadcast bands. The received level is generally varying with daytime.

(iii) **Periodic impulsive noise asynchronous to the mains frequency:** These types of impulses have in most cases a repetition rate between 50 kHz to 200 kHz, which results in a spectrum with discrete lines with a frequency spacing according to the repetition rate. This type of noise is mostly caused by switching power supplies.

(iv) **Periodic impulsive noise synchronous to the mains frequency**: These impulses have a repetition rate of 50Hz or 100 Hz and are synchronous to the mains cycle. They are of short duration (some microseconds) and have a psd decreasing with frequency. This type of noise is caused by power supplies operating synchronously with the mains cycle.

(v) **Asynchronous impulsive noise:** Asynchronous impulsive noise is caused by switching transients in the network. The impulses have durations of some microseconds up to a few milliseconds with random arrival times. The psd of this type of noise can reach values of more than 50 dB above the background noise.

The noise types 1-3 usually remain stationary over periods of seconds and minutes or sometimes even for hours, and may be summarized as background noise. The noise types four and five, however, are time variant in terms of microseconds and milliseconds. During the occurrence of such impulses the psd of the noise is perceptibly higher and may cause bit or burst errors in data transmission. [17]

## 1.6 Modulation and Multiple Access techniques in PLC:

Different types of transmission schemes have been investigated to cope with PLC channel impairments. The next sections give a brief description of the most common cases.

### 1.6.1 Different Modulation Schemes

Different modulation schemes that are found suitable for PLC are,

- Single Carrier (SC) Modulation: Examples are BPSK, FM etc.
- Multi-Carrier (MC) Modulation: Examples are DMT, OFDM etc.

Single-carrier modulations are the simplest approach. Though, their use is disallowed due to two main factors. Firstly, because of the severe inter-symbol interference (ISI) caused by the strong dependence of the attenuation with frequency which obliges to employ complex equalization and detection structures. Besides, the classical Viterbi sequence detector is not appropriate because its computational complexity increases exponentially with the impulse response length, which is quite large in power-line channels. In addition, the short symbol periods needed to attain high bit rates makes these modulations extremely vulnerable to impulsive noise. Furthermore, since spectral resources are separate because of EMC constraints, a single-carrier modulation is not the best suited scheme to make the most from the channel.

Multicarrier modulations are considered to be the most appropriate transmission techniques for broadband PLC. Orthogonal Frequency Division Multiplexing (OFDM) is considered as the modulation scheme for broadband power line communication by most researchers. By the application of OFDM, the most distinct property of power-line channel, its frequency selectivity, can be easily coped with. Accordingly, leading modem manufacturers in this area have selected OFDM, one of their two most common forms along with Discrete Multi-Tone (DMT), for their physical layers implementation. The basic principle is to divide the available spectrum into subbands or subchannels. Hence, a frequency selective channel is transformed into a set of parallel flat channels in which equalization is easily accomplished by means of a one-tap frequency equalizer (FEQ). By using the so-called bit-loading, the assemblage employed in each subband can be chosen independently according to its particular channel conditions. Those subbands with EMC problems or deep notches are left unused. Therefore, spectral resources can be fully exploited even if they are light. An additional consequence of the division into parallel subchannels is that the symbol length becomes longer. Hence, their sensitivity to impulsive noise and ISI is reduced. On the other hand, the decoding delay increases (although it still remains acceptable for most applications) and, as the resulting signal is the sum of a large number of independent components, it exhibits a large peak-to-average ratio (PAR). Furthermore, considerable interference may also arise in an asynchronous multiuser environment.

The OFDM transmission scheme has the following key advantages:

- OFDM is an efficient way to deal with multipath; for a given delay spread, the implementation complexity is significantly lower than that of a single-carrier system with an equalizer.
- Makes efficient use of the spectrum by allowing overlap.
- In relatively slow time-varying channels, it is possible to enhance capacity significantly by adapting the data rate per single-carrier system according to the signal-to-noise ratio (SNR) of that particular single-carrier system.
- OFDM is robust against narrowband interference because such interference affects only a small percentage of the single-carrier systems.
- OFDM makes single-frequency networks possible, which is especially attractive for broadcasting applications [4].
- Cyclic prefix is a crucial feature of OFDM used to combat the inter-symbol interference (ISI) and inter-channel-interference (ICI) introduced by the multi-path channel through which the signal is propagated.
- Using adequate channel coding and interleaving one can recover symbols lost due to the frequency selectivity of the channel.
- It is possible to use maximum likelihood decoding with reasonable complexity.

- OFDM is computationally efficient by using FFT techniques to implement the modulation and demodulation functions.
- Provides good protection against co channel interference and impulsive parasitic noise.
- OFDM is more sensitive to frequency offset and phase noise.
- OFDM has a relatively large peak-to-average-power ratio, which tends to reduce the power efficiency of the radio frequency (RF) amplifier [28-29].

Besides OFDM also has some drawbacks compared with single carrier modulation:

- OFDM is more sensitive to frequency offset and phase noise.
- OFDM has a relatively large peak-to-average-power ratio, which tends to reduce the power efficiency of the radio frequency (RF) amplifier [4].

### 1.6.2 Different Multiple Access Schemes

There are different multiple access techniques that are adopted such as CDMA, MC-CDMA, TDMA, FDMA etc.

Spread spectrum modulations and their natural multiple access technique, Code Division Multiple Access (CDMA), have aroused considerable interest in the last years [32] [33]. In fact, commercial solutions using these strategies are currently available. The low PSD of the transmitted signal, required to comply with the EMC regulations, and their greater immunity to multipath fading, compared to single-carrier systems, make them adequate candidates for PLC. On the other hand, they do not take advantage of the spectral shaping of the power-line channel, in which signal-to-noise ratio (SNR) differences among bands may be up to 40dB. Powerful equalization schemes are also required. In addition, orthogonal codes and perfect synchronization are needed to avoid the near-far effect that arises in multiuser environments, where the desired signal received from a distant user may be completely hidden by the interference caused by a closer transmitter. Spread spectrum modulations seem to be an interesting solution, in terms of implementation complexity, for moderate to low data rates. CDMA is an attractive scheme due to robustness to interferences, which is very important in broadband power line communications since there are two sources of interference, the interference from other wireless devices and the multiuser interference in a home-network. A combination of multicarrier modulation and CDMA, MC-CDMA has the advantages of both techniques. Multicarrier system can perform better than single carrier modulation in presence of impulsive noise, because it spreads the effect of impulsive noise over multiple subcarriers [9]. Like other communication systems, coding can improve the multicarrier system performance but because of the nature of this channel the achieved improvements are usually very restricted. Therefore, analysis of coded and uncoded multicarrier communication scheme in this hostile environment seems to be necessary in order to offer some insight about the overall performance and achievable improvements for this system [34].

The straightest one is to use a TDMA scheme with a random access algorithm, similar to the carrier sense multiple access with collision avoidance (CSMA/CA) used in the IEEE 802.11 wireless LAN standard. This scheme is very simple but, since it does not take into consideration link characteristics, it may result in a quite unfair sharing of the medium. In addition, it does not provide the quality of service (QoS) required by multimedia applications. To avoid this end, centralized TDMA schemes have been investigated [33]. The basic idea is to establish special time intervals in which users exchange information about their profiles (e.g. performance of their channels, requested bit rate and priority) and, according to an allocation algorithm, a central node computes the time slot distribution. Alternative hybrid solutions with both CSMA and contention free periods have also been proposed. Nevertheless, since unused carriers in a certain link (because of low SNR) may experience acceptable SNR in other links, the preceding schemes actually waste capacity. Hence, a straightforward extension would be to allow a secondary user to utilize the remaining carriers. The price to be paid is the increment in the signaling among users and the multiple access interference (MAI) that the secondary user may cause on the primary one.

The above strategy is just an intermediate step towards a frequency division multiple access (FDMA). This process is particularly efficient when employing OFDM or DMT because bands assigned to different users overlap. In the particular case of DMT, carriers allocated to different users can be theoretically separated without the need for an analog filtering by means of the DFT. This process is sometimes referred to as digital band separation and is done at the cost of increasing the number of bits of the ADC. Despite this fact, DMT-FDMA has some additional drawbacks. Firstly, synchronization among users is required to avoid severe MAI. Furthermore, even in the case of synchronized transmissions, the frequency selectivity of the channel causes MAI. Secondly, the optimum carrier allocation scheme is a non-linear optimization problem with thousands of unknowns. Although this problem is usually tackled by means of suboptimal linear programming approaches, the MAI dependence on the carrier assignment may require the use of iterative resource allocation procedures. Moreover, the amount of signaling between the users and the centralized manager is considerably high, since per-carrier information must be exchanged. Before the awareness of the channel short-term changes, this was a point in favor of TDMA. However, to cope with these periodic variations, TDMA users must divide the mains cycle into a relatively high number of regions and indicate the bit-rate achieved in these regions to the central node. Hence, this previous advantage of TDMA vanishes in a periodically time-varying channel.

Both TDMA and FDMA can be employed with a time division duplexing (TDD) or a frequency division duplexing (FDD) scheme. Traditionally, traffic asymmetries between both communication directions have been more easily accomplished with the former technique. However, the same flexibility can be obtained with the latter strategy when it is performed by means of the digital band separation. On the other hand, the receiver has to deal with severe echo levels. This is due to the low isolation values provided by the directional coupler employed in the two-wire to four-wire conversion, which in turns is due to the wide range of input impedance values presented by the power grid. As a consequence, the required resolution of the analog-to-digital converter (ADC) might be notably increased.

## 1.7 PLC System with Diversity

In telecommunications, a diversity scheme refers to a method for improving the reliability of a message signal by using two or more communication channels with different characteristics. Diversity plays an important role in mitigating fading and co-channel interference and avoiding error bursts.

In wireless communication, Diversity scheme is using for the following facts:

i. By increasing the transmitted signal power, we can’t simply overcome the degradation of transmission quality due to channel fading. Because even with high transmitted power, if the channel is in deep fading, the instantaneously received SNR per bit can still be very low, which results in a high probability of transmission error during the deep fading period.
ii. Hand-held subscriber equipments have limited capacity in the batteries which results in a limited power available on the reverse link in wireless communications. By using diversity, the required transmitted power can be greatly reduced.
iii. There are severe different types of interference in cellular communications. By using diversity reception, the channel fading can be mitigated that can translate into improved interference tolerance which in turn, means a greater ability to support additional users and therefore higher system capacity [2].

Some different types of diversity schemes are discussed in below:

### 1.7.1 Frequency Diversity:

In frequency diversity, the signal is transferred using several frequency channels or spread over a wide spectrum that is affected by frequency selective fading. The separation between adjacent frequency slots should be larger than the channel coherence bandwidth such that channel fading over each slot is independent if that in any other slot. By using redundant signal transmission, this diversity improves link transmission quality at the cost of extra frequency bandwidth.

**1.7.2 Time Diversity**:

In time diversity, multiple versions of the same signal are transmitted at different time instants. The time separation between adjacent transmissions should be larger than the channel coherence time such that the channel fading experienced by each transmission is independent of the channel fading experience by all of the other transmissions. Alternatively, a redundant forward error correction code is added and the message is spread in time by means of bit-interleaving before it is transmitted. Thus, error bursts are avoided, which simplifies the error correction.

**1.7.3 Space Diversity**:

The signal is transmitted over several different propagation paths. In the case of wired transmission, this can be achieved by transmitting via multiple wires. In the case of wireless transmission, it can be achieved by antenna diversity using multiple transmitter antennas (transmit diversity) and/or multiple receiving antennas (reception diversity). In the later case, a diversity combining technique is applied before further signal processing takes place. If the antennas are far apart, for example at different cellular base station sites or WLAN access points, this is called macrodiversity or site diversity. If the antennas are at a distance in the order of one wavelength, this is called microdiversity. A special case is phased antenna arrays, which also can be used for beam forming, MIMO channels and space–time coding (STC).

**1.7.4 Polarization Diversity**:

The desired message is received simultaneously by several directive antennas pointing in widely different directions. The received signal consists of scattering waves coming from all directions. It has been observed that the scattered signals associated with the different (non overlapping) directions are uncorrelated. Polarization diversity can be viewed as a special case of space diversity as it also required multiple number of antennas.

**1.7.5 Path Diversity**:

In CDMA cellular networks, the use of direct sequence spread spectrum modulation techniques permits the desired signal to be transmitted over a frequency bandwidth much larger than the channel coherence bandwidth. The spread spectrum signal can resolve multipath signal components as long as the path delays are separated by at least one chip period. A Rake receiver can separate the received signal components from different propagation paths by using code correlation and can then combine the signal components constructively. In CDMA, exploiting the path diversity reduces the transmitted power needed and increases the system capacity.

### 1.7.6 Multiuser Diversity:

Multiuser diversity is obtained by opportunistic user scheduling at either the transmitter or the receiver. Opportunistic user scheduling is as follows: at any given time, the transmitter selects the best user among candidate receivers according to the qualities of each channel between the transmitter and each receiver. A receiver must feed back the channel quality information to the transmitter using limited levels of resolution, in order for the transmitter to implement Multiuser diversity.

## 1.8 Diversity Combining:

Diversity combining is the technique applied to combine the multiple received signals of a diversity reception device into a single improved signal. Various methods have been proposed for combining independently faded signal components and the difference between these methods is the receiver complexity versus transmission performance improvement. Some different diversity combining techniques are discussed in brief as follows:

- **Equal-gain combining:** In equal gain combining, all the signals are weighted equally after coherent detection which removes the phase distortion. The coherently detected signals from all the branches are simply added and applied to the decision device. As the receiver does not need to estimate the amplitude fading, EGC is much simpler compare to the others combining schemes.
- **Maximal-ratio combining**: Maximal-ratio combining (MRC) is a method of diversity combining in which the signals from each channel are added together, the gain of each channel is made proportional to the rms signal level and inversely

proportional to the mean square noise level in that channel, different proportionality constants are used for each channel. It is also known as ratio-squared combining and pre-detection combining. Maximal-ratio combining is the optimum combiner for independent AWGN channels. MRC can restore a signal to its original shape.

- **Switched combining:** The receiver switches to another signal when the currently selected signal drops below a predefined threshold. This is also often called "Scanning Combining".
- **Selective combining:** In selective combining, the receiver monitors the SNR value of each diversity channel and chooses the one with the maximum SNR value for signal detection. If we compare with the others schemes mentioned before, selective combining is much easier to implement without much performance degradation, especially for the reverse link transmission where the diversity branches can be physically located in different base stations, which would make it difficult to use MRC or EGC [2].

Sometimes more than one combining technique is used. For example, lucky imaging uses selection combining to choose (typically) the best 10% images, followed by equal-gain combining of the selected images.

Other signal combination techniques have been designed for noise reduction and have found applications in single molecule biophysics, chemo-metrics among other disciplines [31].

## 1.9 Review of Previous Works on PLC

In the last few years, considerable researches have been carried out in PLC field both analytically and also by simulations. Several techniques have been introduced to model the transfer characteristics of power lines. Basically, there are two essential factors in these models: the model parameters and the modeling algorithms. These two factors determine the reliability and accuracy of the model. From the ways the model parameters are obtained, the modeling technique can be classified into two approaches: the top-down approach and the bottom-up approach. In the top-down approach, the model parameters are retrieved from measurements [35-37]. This approach requires little computation and is easy to implement. However, since the parameters depend on the measurement results, the model is prone to measurement errors. On the contrary, the bottom-up approach starts from theoretical derivation of model parameters [8-9], [38-39]. Although this approach requires more computational efforts comparing to the top-down approach, it however describes clearly the relationship between the network behavior and the model parameters. Moreover, this modeling approach is more adaptable and flexible since all the parameters are formulated, making it easy to predict the changes in the transfer function should there be any change in the system configuration.

Some measurement based analytical models have been developed describing complex transfer functions of powerline networks using only a small set of parameters which is based on physical signal propagation effects in mains networks including numerous branches and impedance mismatching [10] [16-17]. This model is suitable for performance analysis of typical powerline networks [36].

As the power-line channel does not represent an additive white Gaussian noise (AWGN) environment, in the frequency range from some KHz up to 20 MHz it is mostly dominated by narrow-band interference and impulsive noise. So noise characteristics are important parameters to describe the nature of power-line communication channel interference. Numerous researches have been done on different types of noises in power-line communication channel, their characteristics and their mathematical model [17] [40-41].

A notable number of works have been done using Orthogonal Frequency Division Multiplexing (OFDM) in power-line communication to mitigate the adverse effect of impulsive noise and multipath and thus improve the Bit Error Rate (BER) performance of PLC system. It is shown that OFDM is a very good solution in power-line communication to improve the BER performance and only the heavily disturbed impulsive noise will interfere the BER performance of the OFDM based PLC system [15] [42-43].

In [44], broadband communications for indoor power-line networks with impulsive noise using Multicarrier CDMA (MC-CDMA) is considered also. The BER performance of the MC-CDMA system under impulsive noise and frequency fading is theoretically analyzed and closed form expression for this performance is derived. Furthermore, a theoretical upper bound for performance of coded MC-CDMA system is derived. In [45], different multiple access techniques for wideband upstream powerline communications such as carrierless/ amplitude phase modulation-CDMA (CAP-CDMA) and discrete multi-tone-FDMA (DMT-FDMA) have been discussed and both schemes have been compared for multiuser transmission over a powerline network.

A remarkable works also have been done using MIMO-OFDM, SIMO, and MISO etc. in PLC [46-47]. In these researches, it is found that BER performance of a PLC system is further improved using both OFDM and MIMO or other techniques. It could be a great option to use both OFDM and multiple receiving antennas together to mitigate the effect of multipath and different types of noises specially impulsive noise in broadband power-line communication system to improve further the BER performance of the respective system.

### 1.10 Objectives of the Thesis

The main objectives of this thesis are:

i. To find the analytical expression for the OFDM signal at the receiver output taking into account the multipath propagation, the load impedance and the number of branches in a power line network.

ii. To carry out the analysis to find the expression for interference due to channel impairments and the signal to interference plus noise ratio (SINR) for a given set of network parameters.

iii. To extend the analysis for multiple receiving antennas with maximal ratio combining technique and to find the expression and the BER for OFDM carrier including above effects.

iv. To evaluate the Bit Error Rate (BER) performance results for a practical BPLC system numerically and to find the limitations imposed by multipath propagation and load impedance with power line transfer function on the link BER performance. Also to determine the optimum power line network system parameters for a given data rate and BER.

The outcome of this thesis is to evaluate the expression of BER for OFDM carriers including the load impedance and transmission line effects and to explore a model with multiple receiver antennas that will be useful to mitigate these effects and improve the BER performance of the respective OFDM BPLC system.

### 1.11 Outline of Methodology

In this thesis work, an analytical model of multipath propagation due to reflection for different branches of a power line network will be considered for a given number of branches and load impedance. The analytical expression of the signal at the receiving end will then be developed considering multicarrier modulation using OFDM. The expression of the interference among the multiple carriers due to multipath propagation will be developed. The effect of noise will be included in the analysis considering Gaussian impulsive noise model as reported in literature. The expressions for signal power and interference power and the signal to noise plus interference ratio (SINR) will then be developed. The analysis will be extended with multiple receiving antennas to find the expression of the output of the combiner considering Maximal ratio Receiver Combining (MRRC) scheme. The PDF of the noise at the output of the combiner will be developed along with the output SINR. The bit error rat will be evaluated following standard BER expression for OFDM carriers. The computations of BER will be carried out for different multipath propagation models and different power line branches and load impedance values and channel transfer function. Optimum system design parameters will be determined for a given Bit rate and BER.

**1.12 Organization of the Thesis:**

Chapter 1 provides a brief description of Power Line Communication system, brief history of PLC and its operating principle. Different types of noise, their behaviors, different types of diversity schemes, different types of modulation and multiple access schemes, merits and limitations of OFDM, etc. are discussed also briefly. Finally, the objectives and methodology of this thesis are outlined in this chapter.

Chapter 2 depicts the theoretical analysis of the BER performance of an OFDM based PLC system with and without fading, with different noise models and multipath propagation. Multipath model for the powerline channel proposed by Zimmerman-Dostert is considered. Expression of SNR from BER is also developed and presented in this chapter. Finally, theoretical analyses are provided without and with receive diversity considering MRC (maximal ratio combining) scheme.

Following the theoretical analysis presented in Chapter-2, the performance results of the OFDM based BPLC system are evaluated numerically with single and multiple receiving antennas using maximal ratio combining (MRC) technique. Results are depicted in terms of SNR and BER for several system parameters. Finally, the improvement in performance due to diversity is determined along with optimum system parameters.

Chapter 4 provides the concluding remarks and the possible future works, followed by references.

# Chapter 2

## Theoretical Analysis of an OFDM Broadband Power Line Communication System with Multiple Receiving Antennas

### 2.1 Introduction:

Power Line networks offer a convenient and cheap communication media due to its universal existence in buildings and residences, low cost of installation, the availability of outlets, and the simplicity of the power plug. The idea of using the electric power distribution grid for communication purposes is not new at all. For many decades power supply companies have been using their networks for data transmission, even if the main purpose has been management, control and supervision of power plants and distribution facility operations, tasks that call for rather low data rates in the kbit/s range. A next level is the exploitation of the power supply grid for in-home networking purposes, i.e., fast Internet access, voice over IP and home entertainment, tasks requiring data rates in excess of 100 Mbit/s [40].

However, the characteristics of power line channels create some technical challenges for high-speed broadband communications as power lines are not specifically designed for data communication purposes. The most crucial channel properties degrading the performance of high-speed communications over power lines are noise, attenuation and multipath propagation. In any given power line channel (medium voltage or low voltage or indoor), the number of interconnected branches in the link between sending and receiving ends, different terminal loads and branch lengths cause multipath (due to transmission and reflection of signals between the transmission line segments) characteristics that are similar to wireless channel. This multipath causes degradation of the signals propagating in the link between the sending and receiving ends [15].

To cope with this behaviour, a very useful technique is Orthogonal Frequency Division Multiplexing (OFDM) because OFDM can perform better than single carrier when the channel is interfered by impulsive noise, because it spreads the effect of impulsive noise over multiple symbols due to discrete Fourier transform (DFT) algorithm. It also permits to separate overall transmitted data in many parallel independent subcarriers. The long symbol duration time makes OFDM to perform better than single carrier under the multipath effect also. There have been various studies on the channel performance based on OFDM systems [15], [42]. Many studies on the channel performance have focused on impulsive noise and some were based on multipath and impulsive noise using the Middleton Class A noise model [56-57]. However, most of the existing studies which involve either additive white Gaussian noise (AWGN), with or without impulsive noise mainly tend to derive the transfer function of the respective model rather than determining BER performance of the system without receiver diversity.

Signal degradation in a power line communication due to multipath fading, time dispersion etc. can be improved by diversity technique, too [2]. The basic concept of diversity is that the receiver has more than one number of transmitted signals available and each of the transmitted signals is received through a separate channel. When several number of individual channel carrying the same information are received over multiple channels that exhibit independent fading with comparable strengths, the chances that all the independently faded signal simultaneously are greatly reduced [1-3].

Therefore, it is important to investigate the BER performance of a power line communication system considering single and multiple receiving antenna under the influence of the above channel limitations.

## 2.2 Power Line Channel Model

The development of new communication systems requires a comprehensive knowledge of the characteristics of the transmission medium. The selection of the transmission technique and other design parameters is based on the channel transfer properties and the capacity offered by the channel. This calls for suitable models that can describe, with sufficient precision, the transmission behavior over the communication channel. The power line channel was not designed for high-speed data transmission communications, hence modeling this channel is a very difficult task and forms one of the major technical challenges. In addition to the impulsive noise problem that will be discussed in the following section, power lines exhibit strong branching due to their complicated distribution structures, leading to a significant degradation of transmission quality. Signal propagation along power lines does not only take a single path from the transmitter to the receiver. Reflections from load points lead to the reception of multiple delayed versions (echoes) of the transmitted signal.

A simple schematic diagram for power line network is shown below with one branch and also with multiple branches which are distributed. Though the branches could be either concentrated at a given node or distributed in the link between the transmitting and the receiving end.

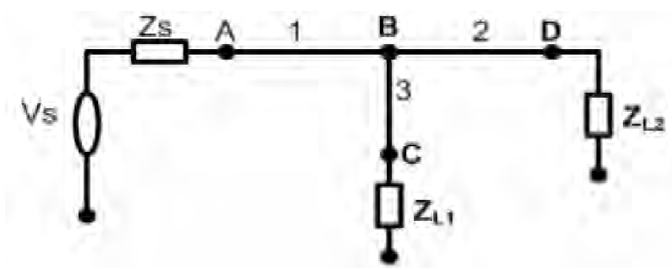


Fig. 2.1: Power line Network Configuration with one branch

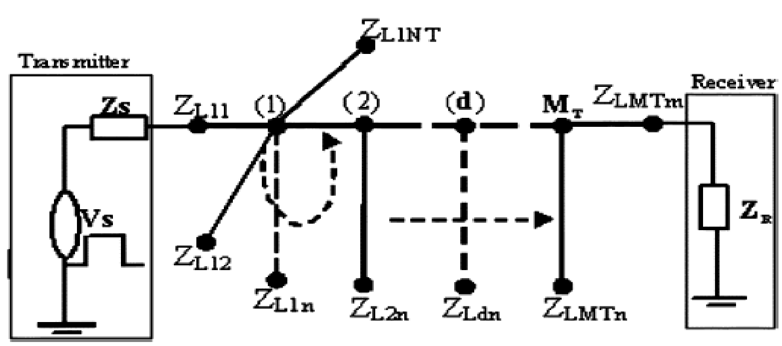


Fig. 2.2: Power line Network with distributed branches

Several attempts to model the power line can be found in the literature (e.g. [8], [10], [48]). On the other hand, existing models for the transfer function of power lines are based on two fundamental approaches: time domain and frequency domain [49]. Time domain models are generally based on measurement trials and averaging of the obtained results. Frequency domain models, on the other hand, are based on a deterministic approach. The two approaches are briefly discussed in the following two sections.

### 2.2.1 Frequency Domain Approach: Transmission Line Models

The power line channel can be modeled using a deterministic approach given a detailed knowledge of the communication link between the transmitter and the receiver. This includes knowledge of the topology, physical properties of the cable, load impedances and so onwards. In the following, models based on the two-conductor and multi-conductor transmission line (MTL) theory are briefly reviewed [49].

#### 2.2.1.1 Two-conductor transmission line models

Several attempts to utilize the two-conductor transmission line theory in modelling the power line channel can be found in the literature [8]. These models use either scattering or transmission matrices [49]. A two-conductor transmission line, with ground being the second conductor, supports four modes of signal propagation. The signal travels along the line in two spatial modes each having two directions of propagation [49]. The two spatial modes are the differential and common modes. The dominant mode carrying the data signal in the desired direction along the transmission line is the differential mode. Differential signaling can be used to excite the propagation in the differential mode only, and minimize the propagation in the common mode which is normally induced by external noise. To achieve good rejection of unwanted external signals, the two conductors must be well balanced as any imbalance between them excites common mode propagation. The two-conductor model did not address the effects of wiring and grounding practices in the transmission behaviour. In addition to this, the model neglected the effect of electromagnetic compatibility that could be a issue in the estimation of the common mode currents. Moreover, the two-conductor model does not explain the propagation in the presence of a third conductor as appears in single-phase power lines, leading to a MTL situation. Therefore, the attempts to model the power line channel based on a two-conductor transmission line approach did not fully explain the propagation behaviour along power lines (e.g. [8],[49]).

Cross-sectional view of the house service power line and the equivalent lumped element circuit of a Two-wire transmission line are shown below:

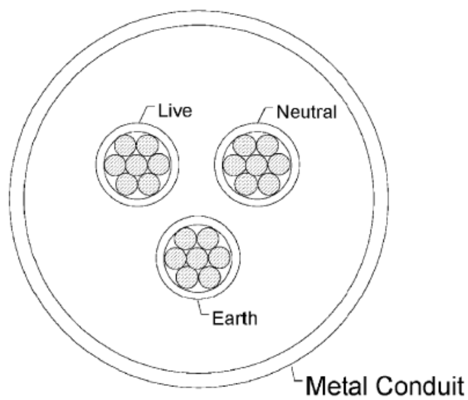


Fig. 2.3: Cross-sectional view of the House Service Power Line

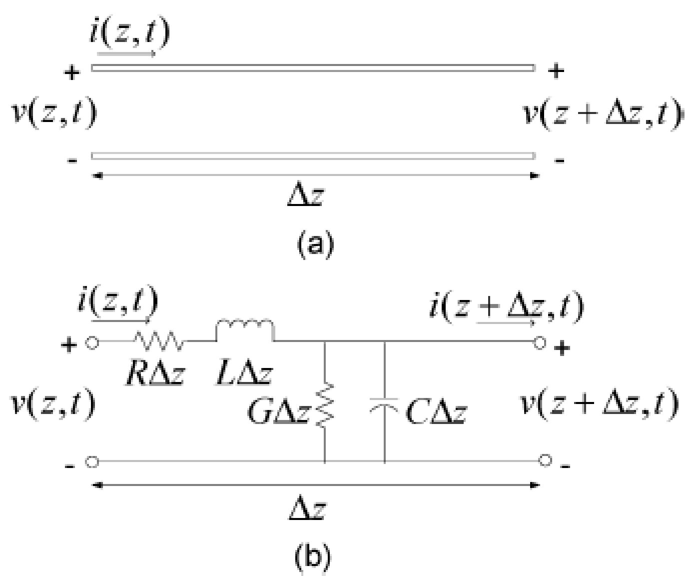


Fig. 2.4 (a) The Voltage and Current definitions of Two-wire transmission line (b) The equivalent lumped element circuit

#### 2.2.1.2 Multi-conductor transmission line (MTL) models

Power cable used in single-phase connections consists of three or four conductors, which limits the applicability of the two-conductor transmission line model in explaining the propagation scenario. Therefore, the modeling of the power line channel in the presence of a third or fourth conductor should rather utilize MTL theory. In MTL, a transmission line consisting of N conductors and a ground is partitioned into N simple transmission lines, each representing a single propagation mode [50]. Accordingly, the signal at the input of an MTL is broken into N modal components, each of which travels along the corresponding modal TL. The modal components of the signal are recombined at the output ports. The coupling between each port and each modal TL is obtained using the weighting factors in the voltage and current transformation matrices.

If a three-conductor power cable is used, then six propagation modes exist in the line resulting from three spatial modes (i.e. differential, pair and common). Each of the three spatial modes has two directions of propagation. The desired signal current generally travels in the differential mode. The signal in the pair-mode corresponds to the current flowing from the ground wire and the other two wires, whereas the signal in the common mode of propagation corresponds to the overall imbalance between the modes and is directly related to the cable installation practices [51]. In indoor PLC systems, there is often an imbalance between the propagation modes which results in coupling between the modes [51].

Frequency-domain channel models based on transmission line theory offer the advantage of low computational complexity that is almost independent of the power line link topology [49]. Though, full and detailed knowledge of the transmission link must be available before modeling. The model requires details about the topology, properties of the cables used and impedance values at the end of every branch involved. The accuracy of the model can be significantly affected if perfect knowledge of such parameters is not available. In a practical scenario, such knowledge of the power line network is nearly impossible, which makes modeling the power line channel using frequency domain models based on transmission line theory unrealistic. The time-domain approach described in the next section, however, does not require such details about the network. For this reason, the time-domain multipath model is preferred over frequency-domain models and it is utilized in this thesis to simulate the communication scenario in power lines.

An equivalent circuit for a semi-infinite three conductor cable is given below:

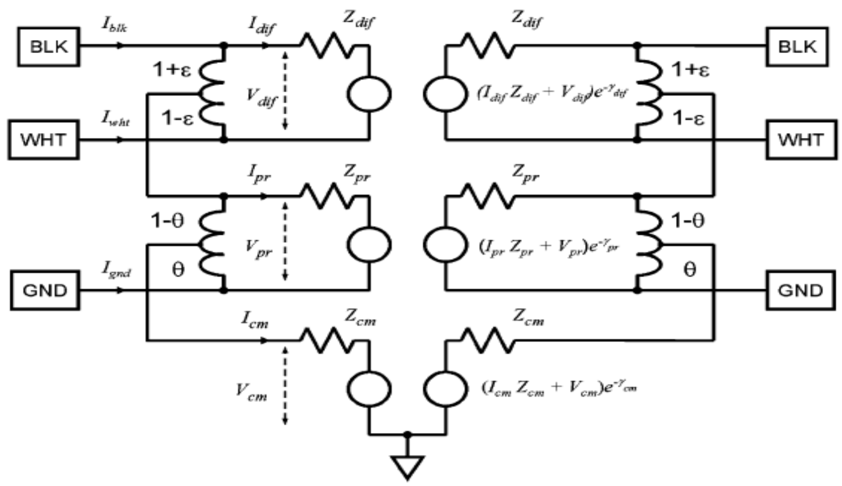


Fig. 2.5: Equivalent circuit for a semi-infinite three-conductor cable

### 2.2.2 Time Domain Approach: The Multipath Model

The topology and structure of power line grids are different from telecommunications networks. In power line networks, the link between a substation and the customer's premises is not presented by a point-to-point connection as in the case of communications networks such as telephone local loops. The link from a transformer substation consists of a distribution link forming a bus topology and house connections with various lengths representing branches from the distributor cable. The house connection is terminated at a house connection box followed by numerous branches in the in-house wiring. Branching and impedance mismatches in the power line network cause frequent reflections leading to a multipath propagation scenario with frequency selectivity. Moreover, frequency-dependant attenuation has to be considered when modeling the power line channel.

Signal attenuation in power lines is the result of coupling losses which depend on the PLC transmitter design and line losses depending on the length of the cable [52]. In addition to the frequency-dependent attenuation, the channel transfer function is also time-varying and depends on the location of the receiver since different appliances are constantly being switched on or off causing changes in the transfer function. Models of the power line channel transfer function that describes the multipath propagation effects have been proposed by Philipps [48] and Zimmermann and Dostert [10], [36].

#### 2.2.2.1 A Multipath Model for the Power Line Channel:

The powerline "local loop access network" does not consist of point-to-point connections between substations and customer's premises, but represents a line bus, which is opposite to the telephone copper loop. A typical access link between a substation and a customer consists of the distributor cable, or a series connection of distributor cables, and the branching house connection cables, both with a real valued characteristic impedance $Z_L$. The house connection cables are terminated at a house connection box, followed by the indoor wiring, which can be modeled from the point of view of the access network by a complex termination impedance $\underline{Z}_H(f)$. The impedance of the house connection point is usually low due to numerous branching in-house cables. Moreover, $\underline{Z}_H(f)$ appears very stationary, since the low impedance point hides impedance variations within the indoor network. Numerous reflections are caused by the joints of the house service cables, house connection boxes, and the joints at series connections of cables with different characteristic impedance [10], [36].

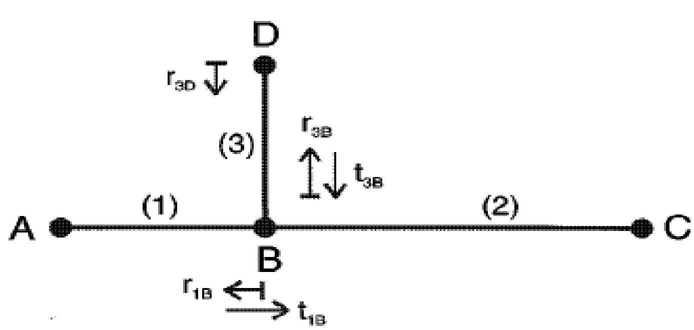


Fig. 2.6: Multipath signal propagation; cable with one tap

*Multipath Signal Propagation*

Signal propagation does not only take place along a direct line-of-sight path between transmitter and receiver, but additional paths (echoes) must also be considered. The result is a multipath scenario with frequency selective fading. Multipath signal propagation is studied by a simple example which can be easily analyzed (Fig. 2.6). The link has only one branch and consists of the segments (1), (2), and (3) with the lengths $l_1$, $l_2$ and $l_3$ and the characteristic impedances $Z_{L1}$, $Z_{L2}$ and $Z_{L3}$.

In order to simplify the considerations, A and C are assumed to be matched, which means $Z_A = Z_{L1}$ and $Z_C = Z_{L2}$. The remaining points for reflections are B and D, with the reflection factors denoted as $r_{1B}$, $r_{3D}$, $r_{3B}$, and the transmission factors denoted as $t_{1B}$, $t_{3B}$. With these assumptions, an infinite number of propagation paths is possible in principle, due to multiple reflections (i.e. $A \to B \to C$, $A \to B \to D \to B \to C$, $A \to B \to D \to B \to D \to B \to C$, and so on). Each path $i$ has a weighting factor, representing the product of the reflection and transmission factors along the path. All reflection and transmission factors at powerlines are basically less or equal to one. This is due to the fact that transmission occurs only at joints, where the load of a parallel connection of two or more cables leads to a resulting impedance being lower than the characteristic impedance of the feeding cable. Hence, the weighting factor $g_i$. a product of transmission and reflection factors is also less or equal to one, i.e.,

$$|g_i| \leq 1 \tag{2.1}$$

The more transmissions and reflections occur along a path, the smaller the weighting factor $g_i$ will be. In addition, longer paths exhibit higher attenuation, so that they contribute less to the overall signal at the receiving point. Due to these facts, it is reasonable to approximate the basically infinite number of paths by only N dominant paths, and to make N as small as possible.

The delay $\tau_i$ of a path

$$\tau_i = \frac{d_i\sqrt{\varepsilon_r}}{c_0} = \frac{d_i}{v_P} \tag{2.2}$$

can be calculated from the dielectric constant $\varepsilon_r$ of the insulating material, the speed of light $c_0$, and the lengths $d_i$ of the cables.

The losses of cables cause an attenuation $A(f,d)$ increasing with length and frequency. The signal components of the individual paths have to be combined by superposition. Therefore, the frequency response from *A* to *C* can be expressed as

$$H(f) = \sum_{i=1}^{N} g_i . A(f, d_i) . e^{-j2\pi f \tau_i} \tag{2.3}$$

Signal propagation in more complicated networks with more branches can be partitioned into appropriate paths in a similar way [10].

<u>*Cable Losses*</u>

As mentioned above, the propagating signals are affected by attenuation increasing with length and frequency. This section gives a closer look at the losses and derives a corresponding mathematical model.

The frequency response $H(f)$ of a matched transmission line of length can be expressed, by means of the complex propagation constant

$$\underline{\gamma} = \sqrt{(R'+j\omega L')(G'+j\omega C')} = \alpha + j\beta \tag{2.4}$$

depending on the primary cable parameters *R'*, *G'*, *C'*, and *L'* and the voltage *U(x)* at distance *x*, as follows:

$$H(f) = \frac{U(x=l)}{U(x=0)} = e^{-\underline{\gamma}.l} = e^{-\alpha(f).l}.e^{-j\beta(f).l} \tag{2.5}$$

The cable parameters *C'* and *L'* in equation (2.4) have been roughly estimated by the geometric dimensions and some material properties. Considering frequencies in the MHz range, due to the skin-effect the resistance per unit length *R'* is thus proportional to $\sqrt{f}$ . The conductance per unit length *G'* is mainly influenced by the dissipation factor of the dielectric material (usually PVC) and therefore proportional to *f*. With typical geometry and material properties, we have $R' << \omega L'$ and $G' << \omega C'$ in the frequency range of interest. Hence, the cables can be regarded as weakly lossy with a real valued characteristic impedance $Z_L$. The complex propagation constant can be determined using the simplified expression

$$\underline{\gamma} = \underbrace{k_1\sqrt{f} + k_2 f}_{\mathrm{Re}(\underline{\gamma})=\alpha} + j\underbrace{k_3 . f}_{\mathrm{Im}(\underline{\gamma})=\beta} \tag{2.6}$$

with the constants $k_1$, $k_2$, and $k_3$ summarizing material and geometry parameters. The real part of the propagation constant, the attenuation factor $\alpha$, increases with frequency. However, the exact relation between $\alpha$ and *f* for a special cable can be proportional to $\sqrt{f}$ , to *f*, or to a mixture of both, depending on either $k_1$ or $k_2$ being dominant.

Based on these derivations and extensive investigations of measured frequency responses, an approximating formula for the attenuation factor $\alpha$ is found in the form

$$\alpha(f) = a_0 + a_1.f^{\,k} \tag{2.7}$$

which is able to characterize the attenuation of typical powerline links with only three parameters, being easily derived from the measured transfer functions. By using equation (2.5) and (2.7), the attenuation of a powerline cable can be characterized by

$$A(f,d) = e^{-\alpha(f).d} = e^{-(a_0 + a_1 . f^k).d} \tag{2.8}$$

Although the structure of (2.8) is derived from physical effects, the parameters $a_0$, $a_1$, and $k$ cannot be easily found from previously known cable parameters. This, however, does not limit the value of the model in practice, as it is generally impossible to get all the necessary cable and geometry data for real networks. Typically, the parameters $a_0$, $a_1$, and $k$ are derived from measured transfer functions [10].

**Table 2.1: Parameters of the transfer function of the multipath channel model**

| | |
|---|---|
| $i$ | Number of the path, where the path of the shortest delay has the index *i*=1 |
| $a_0, a_1$ | Attenuation parameters |
| $k$ | Exponent of the attenuation factor (typical values are between 0.5 and 1) |
| $g_i$ | Weighting factor for path *i*, in general complex can be considered as combination of the involved reflection and transmission factors |
| $d_i$ | Length of path *i* |
| $\tau_i$ | Delay of path *i* |
| $c_0$ | The speed of light |
| $\varepsilon_r$ | Dielectric constant of the insulating material |
| $v_p$ | Propagation speed= $c_0 / \sqrt{\varepsilon_r}$ |

### 2.3 Power Line Channel Model

*A. A Generalized Multipath Signal Propagation Model of the Transfer Function*

Combining multipath propagation described by (2.3) and frequency and length depending attenuation given by (2.8) finally leads to

$$\underline{H}(f) = \sum_{i=1}^{P} \underbrace{|g_i(f)| e^{\varphi g_i(f)}}_{\substack{weighting \\ factor}} \underbrace{e^{-(a_0 + a_1 f^k) d_i}}_{\substack{attenuation \\ portion}} \underbrace{e^{-j2\pi f \tau_i}}_{\substack{delay \\ portion}} \qquad (2.9)$$

Equation (2.9) describes the signal propagation along a path by the delay portion and the low-pass characteristic, i.e., the attenuation increasing with length and frequency, by the attenuation portion. The weighting factor $g_i$ summarizes the reflection and transmission factors along a propagation path. Due to the fact that reflection points may exhibit complex and frequency-dependent values, $g_i$ is in general complex and frequency-dependent. The signal components of *P* paths always add together at the receiving point.

*B. Simplified Model*

Extended measurement campaigns revealed that it is possible to further simplify the specification of the weighting factors $g_i$ to being complex, but not frequency-dependent. In many cases of practical interest, $g_i$ can even be assumed as real-valued. In heterogeneous networks, often several paths with almost equal delays exist, so that it is not rewarding to trace the factors $g_i$ back to their physical origins. From a multipath point of view, $g_i$ simply describes the weight of path *i*. Thus, using (2), the final version of the frequency response is given by

$$\underline{H}(f) = \sum_{i=1}^{P} \underbrace{g_i}_{\substack{weighting \\ factor}} \underbrace{e^{-(a_0 + a_1 f^k) d_i}}_{\substack{attenuation \\ portion}} \underbrace{e^{-j2\pi f (d_i / v_p)}}_{\substack{delay \\ portion}} \qquad (2.10)$$

In Equation (2.10), $P$ is the number of multipaths, $g_i$ and $d_i$ are the weighting factor and length of the ith path respectively. $a_0$, $a_1$ and $k$ are the attenuation parameters which can be derived from measured transfer functions.

Equation (2.10) represents a parametric model, describing the complex frequency response of typical powerline channels, covering all considerable effects of the transfer characteristics in the frequency range from 500 kHz to 20 MHz by a small set of parameters, which can be derived from measured frequency responses [10]. The number of paths, $P$, allows a control of the precision of the model, which is especially important for defining reference channels for PLC-system performance analysis.

In the model, the first exponential presents attenuation in the PLC channel, whereas the second exponential, with the propagation speed $v_p$, describes the echo scenario. The attenuation parameters for a 4-path model and a 15-path model were obtained using physical measurements in [10] and are summarized in Tables 2.2 and 2.3 respectively. The simple four-path model covers only the dominant paths of the impulse response while the 15-path model assumes 15 propagation paths and provides more detail and accuracy to the channel transfer function given by (2.10). We'll use both models parameters in our present thesis.

**Table 2.2: Parameters of the Four-path model of the test network [10]**

| Attenuation parameters | | | | | |
|---|---|---|---|---|---|
| $k$=1 | | $a_0$=0 | | $a_1 = 7.8 \cdot 10^{-10}\, s/m$ | |
| Path parameters | | | | | |
| $i$ | $g_i$ | $d_i\,/\,m$ | $i$ | $g_i$ | $d_i\,/\,m$ |
| 1 | 0.64 | 200 | 3 | -0.15 | 244.8 |
| 2 | 0.38 | 222.4 | 4 | 0.05 | 267.5 |

**Table 2.3: Parameters of the 15 path model [10]**

| Attenuation parameters | | | | | |
|---|---|---|---|---|---|
| $k$=1 | | $a_0$=0 | $a_1 = 7.8 \cdot 10^{-10}\, s/m$ | | |
| Path parameters | | | | | |
| $i$ | $g_i$ | $d_i\,/\,m$ | $i$ | $g_i$ | $d_i\,/\,m$ |
| 1 | 0.029 | 90 | 9 | 0.071 | 411 |
| 2 | 0.043 | 102 | 10 | -0.035 | 490 |
| 3 | 0.103 | 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 | | | |

Since positions and depths of notches do not depend on the length of the link, but only on properties of the branches (length and mismatch), it is logical not to consider the impact of notches when specifying a length profile including only basic attenuation characteristics. For finding such length profiles, a 5 path model has been established also in [10], the data of which has been taken from links in German low voltage power distribution networks. The corresponding parameters are listed in Table (2.4). In this model, attenuation parameters $a_0$, $a_1$ and $k$ are variable whether they are constant in 4-path model and 15-path model.

**Table 2.4: Attenuation parameters for a 5-path model [10]**

| Class $d_i$ | $g_1$ | $a_0$ [m$^{-1}$] | $a_1$ [s/m] | $k$ |
|---|---|---|---|---|
| 100 m | 1 | $9.40 \cdot 10^{-3}$ | $4.20 \cdot 10^{-7}$ | 0.7 |
| 150 m | 1 | $1.09 \cdot 10^{-3}$ | $3.36 \cdot 10^{-7}$ | 0.7 |
| 200 m | 1 | $9.33 \cdot 10^{-3}$ | $3.24 \cdot 10^{-7}$ | 0.7 |
| 300 m | 1 | $8.40 \cdot 10^{-3}$ | $3.00 \cdot 10^{-9}$ | 1 |
| 380 m | 1 | $6.20 \cdot 10^{-3}$ | $4.00 \cdot 10^{-9}$ | 1 |

## 2.4 Noise Models for PLC System:

### 2.4.1 Impulsive Noise Model

Asynchronous impulsive noise forms one of the main challenges for highspeed communications over power lines. Practice shows that this type of noise can have large energy leading to a significant degradation in the performance of PLC systems [44], [53]. The fact that impulsive noise may frequently sweep complete data symbols concerns researchers and designers of PLC devices and systems. In [54], practical measurements in power lines found that the typical strength of a single impulse is more than 10 dB above the background noise level and can exceed 40 dB. Measurement results in [55] indicate that the PSD of impulsive noise generally exceeds the PSD of background noise by a minimum of 10-15 dB in most parts of the frequency band 0.2-20 MHz. According to their measurements, this difference may rise to more than 50 dB at certain portions of the band.

Fig. 2.7 shows a sample impulse having duration of approximately 50 $\mu$sec. In the time domain, three random variables characterize the impulsive noise that occurs in power lines and other communication mediums. These are: impulse width, amplitude and inter-arrival time (IAT). Several attempts to derive the probability distribution statistics of these three parameters based on practical measurements in power line networks can be found in the literature [54]. The impulse width and amplitude both identify the energy of a single impulse. The frequencies of the impulses (the reciprocal of the IAT) along with the impulse energy describe the power of impulsive noise. Different statistical approaches attempting to model impulsive noise can be found in the literature. Background noise on the other hand is usually modeled as white Gaussian noise (WGN) [54]. In this section, we look into Middleton Class A noise model to gain more understanding of the characteristics of impulsive noise.

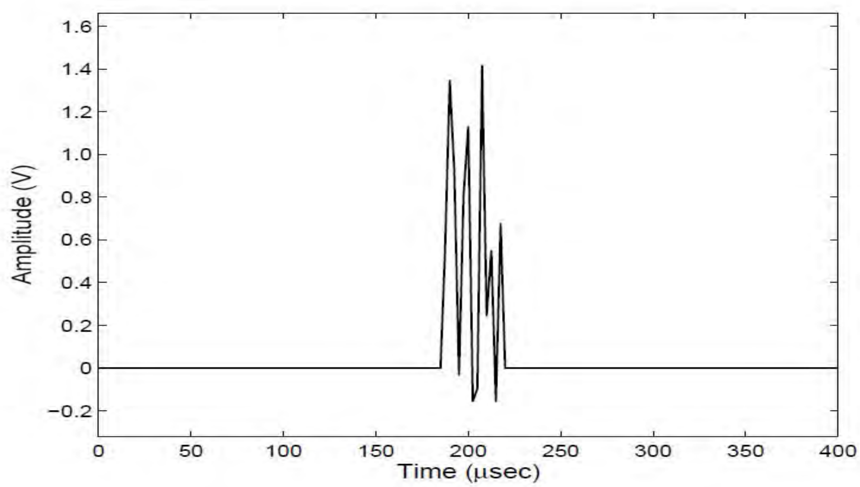


Fig. 2.7: Sample Impulse

**2.4.2 Middleton Class A Noise model:**

Middleton in [56]-[57] classifies the electromagnetic (EM) noise or interference into three main classes: Class A, Class B and Class C (the sum of Class A and Class B). Many researchers consider the Middleton Class A noise model suitable for describing the statistical characteristics of impulsive noise in PLC environments [44] as well as other communication environments. The model incorporates both background and impulsive noises. According to the Middleton Class A model, the overall noise is a sequence of independent and identically distributed (i.i.d.) complex random variables with the probability density function (PDF):

$$p(z)=\sum_{m=0}^{\infty} e^{-A}\frac{A^m}{m!}\frac{1}{2\pi\sigma_m^2}\exp\left(-\frac{z^2}{2\sigma_m^2}\right) \quad (2.11)$$

with the variance $\sigma_m^2$ defined as:

$$\sigma_m^2 = \left(\sigma_g^2+\sigma_i^2\right)\frac{\left(\frac{m}{A}\right)+\Gamma}{1+\Gamma} \quad (2.12)$$

where the parameter $A$ is called the impulsive index and is given by the product of the average rate of impulses per unit time and average impulse duration. The variances $\sigma_g^2$ and $\sigma_i^2$ denote the power of background noise and impulsive noise respectively. The ratio between background noise and impulsive noise power is given by the parameter $\Gamma$. Therefore:

$$\Gamma=\frac{\sigma_g^2}{\sigma_i^2} \quad (2.13)$$

Colored background noise is caused by the superimposition of numerous noise sources, e.g., computers, dimmers or hair dryers, which can create disturbances in the frequency range 0-100 MHz herein considered. Usually it is characterized by a fairly low power spectral density, which, however, significantly increases towards lower frequencies. Although not considered here, narrow band interferences localized in particular frequencies can also be added. They are generated from radio communication devices.

A commonly accepted model is the simple three-parameter model, where the noise is considered Gaussian with the power spectral density (PSD)

$$R_{nb}(f)=a+b\,|\,f\,|^c\left[\frac{dB_m}{Hz}\right] \quad (2.14)$$

where $a$, $b$ and $c$ are parameters derived from measurements and $f$ is the frequency in MHz.

By setting the following parameters $[a, b, c] = [-145, 53.23, -0.337]$ we obtain a worst case scenario, while with the parameters $[a, b, c] = [-140, 38.75, -0.72]$ we obtain a best case scenario. The resulting PSDs are depicted in Fig. 2.8, where the considered frequency band is between 1 MHz and 100 MHz [40].

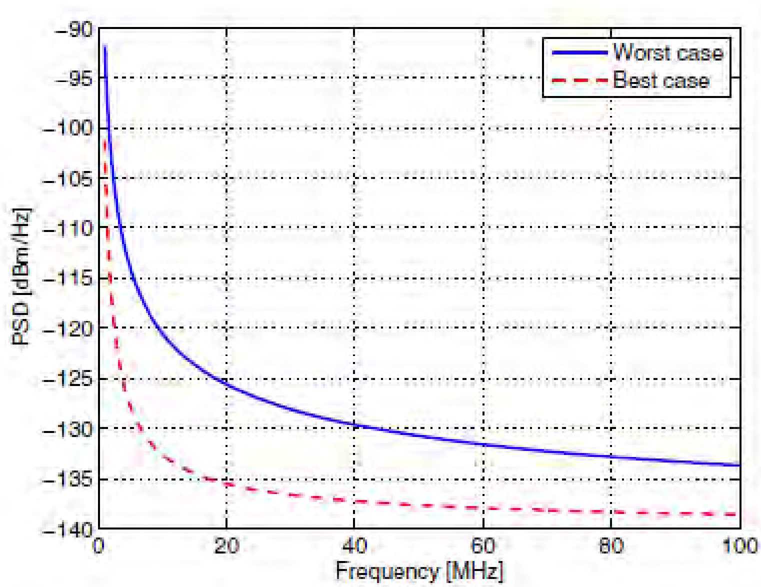


Fig. 2.8: Bad and good background noise PSD

It can be noticed from (2.11) that the PDF of Middleton Class A noise is in fact a weighted sum of Gaussian PDF with mean equal to zero. Therefore the mean and variance of this process can be obtained by the following [24]:

$$\mu_z = E\{z\} = \int z \cdot p(z) \cdot dz = \sum_{m=0}^{\infty} e^{-A} \frac{A^m}{m!} \frac{1}{2\pi\sigma_m^2} \int z \cdot \exp\left(-\frac{z^2}{2\sigma_m^2}\right) = 0 \tag{2.15}$$

$$\sigma_m^2 = E\{z^2\} = \sum_{m=0}^{\infty} e^{-A} \frac{A^m}{m!} \frac{1}{2\pi\sigma_m^2} \int z^2 \cdot \exp\left(-\frac{z^2}{2\sigma_m^2}\right) = \frac{e^{-A}\sigma_g^2}{\Gamma} \sum_{m=0}^{\infty} \frac{A^m}{m!} \left(\frac{m}{A} + \Gamma\right) \tag{2.16}$$

The Middleton Class A noise model was originally developed to describe the man-made EM interference with impulsive behaviour. Despite the fact that this model has been considered by many researchers to depict impulsive noise, its applicability to model impulsive noise in power line networks is inconclusive.

## 2.5 PLC System with OFDM:

OFDM is based on parallel broadband data transmission which reduces the effects of multipath and leads to unnecessary equalization techniques. The general configuration of the OFDM transmission system is represented in Fig. 2.9.

In the transmitter (all of the functional blocks in Fig. 2.9 before the PLC channel), the high-speed data being transmitted are first coded, interleaved, and then mapped. The data are then converted into parallel data and transmitted in several channels. The transmitted data of each parallel subchannel are modulated by either phase-shift keying (PSK) or quadrature amplitude modulation (QAM) [15]. The data are fed into an inverse fast Fourier transform (IFFT) circuit which generates OFDM signals. The signals are fed into a guard-time insertion circuit to reduce inter symbol interference (ISI), which is connected to the channel viz, the PLC channel in our case. Coding is done to make the transmission over the possible real channels and interleaving is done to avoid the long error bursts. Pilot insertion is done to identify the amplitude and the phase reference of the mapping assemblage so that the complex data symbols can be de-mapped correctly

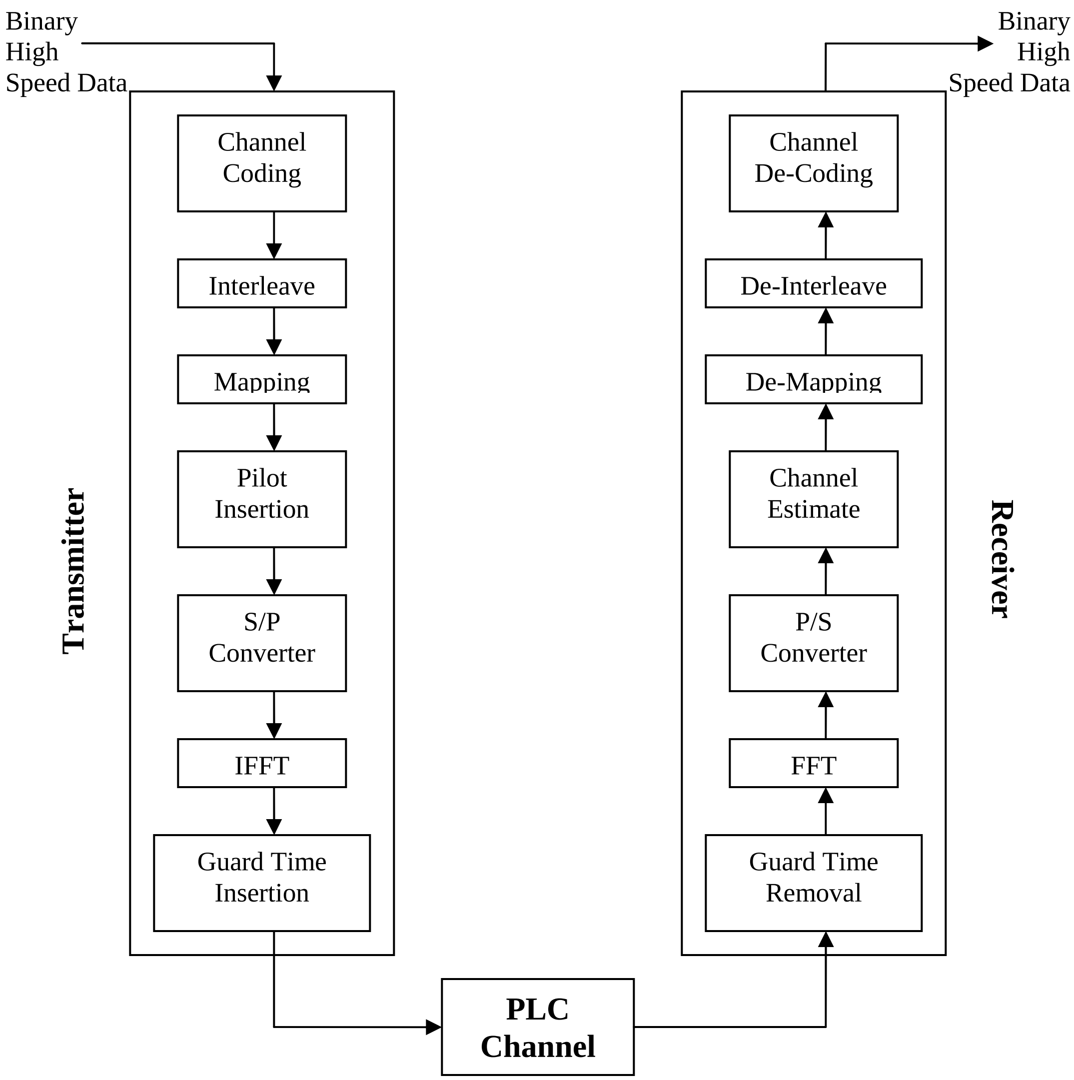


Fig. 2.9: General configuration of the OFDM transmission system.

All of the functional blocks after the channel are referred to as the receiver. In the receiver, the guard time is removed, and the orthogonality of channels is maintained by using the FFT circuit. Since the data in the FFT circuit are parallel, parallel-to-serial conversion is performed by using coherent detection for which channel estimation is necessary. The estimates are necessary so that data can be demodulated correctly.

### 2.6 Bit Error Rate analysis for OFDM BPLC system with single receiver:

The performance evaluation of the modulation scheme in any communication channel is through bit-error rate (BER) performance. OFDM is a block modulation scheme. Let $T_s$ be the symbol intervals of the input source sequence. A block of N serial symbols is converted into a block of B parallel modulated symbols, each of duration $T=NT_s$. If the rms delay spread of the channel is $\sigma_\tau$, N is chosen so that $NT_s >> \sigma_\tau$. This is a means to combat inter symbol interference (ISI) due to channel time dispersion. In the frequency domain, the bandwidth of each subband signal is 1/N times that of the original signal. If the bandwidth of the original signal is large compared with the channel coherence bandwidth, so that the channel exhibits frequency–selective fading, N can be chosen appropriately so that the channel seen by each of the subbands in OFDM exhibits flat fading. Thus OFDM has the property of mitigating frequency-selective fading.

The complex envelope of OFDM is given by

$$v(t) = \sqrt{\frac{2E_b}{T_s}} \sum_{k=0}^{\infty} \sum_{n=0}^{N-1} a_{k,n} \tilde{\varphi}_n (t - kT)$$

$$= \sum_{n=0}^{N-1} v_n (t) \qquad (2.17)$$

Where $a_{k,n}$ carries the information to be sent over the kth symbol interval $t \in [kT, kT + T]$ and the nth subband (n=0,1,2,…,N-1). $v_n(t)$ is the complex envelope of the signal transmitted in the nth subband and is given by

$$v_n (t) = \sqrt{\frac{2E_b}{T_s}} \sum_{k=0}^{\infty} a_{k,n} \tilde{\varphi}_n (t - kT) \qquad (2.18)$$

where $\{\tilde{\varphi}_n (t)\}_{n=0}^{N-1}$ is a set of complex orthogonal waveform and is given by

$$\tilde{\varphi}_n(t) = \begin{cases} \exp\left[ j2\pi \left( n - \frac{N-1}{2} \right) t/T \right], & t \in [0,T] \\ 0 & t \notin [0,T] \end{cases} \qquad (2.19)$$

Each waveform in the set $\{v_n(t)\}_{n=0}^{N-1}$ corresponds to a distinct (nth) subcarrier with frequency $f_c + \frac{2n-(N-1)}{2T}$.

For simplicity, let us consider k=0. We have,

$$v(t) = \sqrt{\frac{2E_b}{T_s}} \sum_{n=0}^{N-1} a_{0,n} \exp\left( j\frac{2\pi nt}{NT_s} \right) \exp\left[ -j\frac{\pi(N-1)t}{NT_s} \right], \quad 0 \le t \le NT_s \qquad (2.20)$$

Here we have to note that the term $\exp\left[ -j\frac{\pi(N-1)t}{NT_s} \right]$ is not a function of n and can be combined with the carrier term $\exp(j2\pi f_c t)$. The complex envelope can thus be written as

$$v(t) = \sqrt{\frac{2E_b}{T_s}} \sum_{n=0}^{N-1} a_{0,n} \exp\left( j\frac{2\pi nt}{NT_s} \right), \quad 0 \le t \le NT_s \qquad (2.21)$$

with corresponding carrier $\exp[j2\pi(f_c - \frac{N-1}{2NT_s})t]$. Sampling *v(t)* at $t = \ell T_s$ yields

$$A_{0,\ell} \approx v(\ell T_s) = \sqrt{\frac{2E_b}{T_s}} \sum_{n=0}^{N-1} a_{0,n} \exp\left( j\frac{2\pi n\ell}{N} \right), \quad \ell = 0,1,2,\ldots,N-1, \qquad (2.22)$$

Which is actually proportional to the inverse discrete Fourier transform (IDFT) of $\{a_{0,n}\}$. The samples, $\vec{A}_0 = (A_{0,1}, A_{0,2}, \ldots, A_{0,N-1})$, are then passed through a digital-to-analog (D/A) converter and are used to modulate the carrier which produces the OFDM signal $x(t) = \Re\{v(t)\exp[j2\pi(f_c - \frac{N-1}{2NT_s})t]$. Let us say, in the OFDM transmitter the input information sequence is partitioned into blocks of length N, each block being represented by $\vec{a}_k, k = 0,1,2,....$.

In general, the received signal is the sum of a linear convolution with the discrete power line channel impulse response *h(t)* and additive white Gaussian noise *n(t)*. For this, we implicitly assume that the channel fading is slow enough to consider it constant during one OFDM symbol. In addition, we assume that the transmitter and receiver are perfectly synchronized. Based on the fact that the cyclic prefix is sufficiently long to accommodate the power line channel impulse response, or *h(t)=0* for *t<0* and *t>N-1*, we can then write,

$$r_k(t) = \sum_{\tau=0}^{N-1} h(\tau)v(t-\tau) + n(t) \tag{2.23}$$

At the receiver, the received signal frequency is first down converted to the baseband and then converted to digital format using an A/D converter. The output sequence of A/D converter is also partitioned into blocks of length N and is demodulated block by block. The corresponding block for k=0 has the following N received samples

$$\vec{r}_0 = (r_{0,0}, r_{0,1}, ..., r_{0,N-1}), \tag{2.24}$$

Demodulation is performed by computing the discrete Fourier transform (DFT) on the block $\vec{r}_0$ to yield N decision variables

$$Z_{0,n} = \frac{1}{N}\sum_{\ell=0}^{N-1} r_{0,\ell} \exp\left(-j\frac{2\pi n\ell}{N}\right), \quad n = 0,1,..., N-1. \tag{2.25}$$

In the OFDM receiver, the decision device estimates the transmitted information $\hat{\bar{a}}_k = (\hat{a}_{k,0}, \hat{a}_{k,1}, ..., \hat{a}_{k,N-1})$, based on the N decision variables $Z_{k,n}$, n=0, 1, …, *N*-1.

The signal to noise ratio (SNR) at the output of k-th subcarrier demodulator is given by [15]

$$\xi_k = |H_k|^2 \alpha_g \cdot \frac{E_b}{N_0} \tag{2.26}$$

where $\alpha_g$ is the guard interval ratio that relates with $T_N$ and $T_{guard}$ as given in equation (2.26).

$$\alpha_g = \frac{T_N}{T_N + T_{guard}} \tag{2.27}$$

The parameters $T_N$ and $T_{guard}$ are information time and guard time of the OFDM symbol [15] as shown in Fig. 2.10

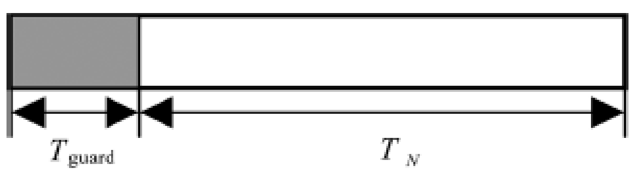


Fig. 2.10: OFDM frame with guard time and symbol duration.

Therefore, the bit error rate (BER) for the k-th subchannel is given by

$$P_{bk} = Q\left(\sqrt{2\xi_k}\right)$$

$$= Q\left(\sqrt{\frac{2|H_k|^2 \alpha_g E_b}{N_0}}\right) \tag{2.28}$$

The parameters $E_b$, $N_0$, $H_k$, and N are the energy of the signal, noise power, subchannel response, and number of subchannels respectively.

Then the average BER can be expressed as:

$$P_b = \frac{1}{N}\sum_{k=0}^{N-1} Q\left(\sqrt{\frac{2|H_k|^2 \alpha_g E_b}{N_0}}\right) \tag{2.29}$$

**2.7 Analysis of PLC System with Multiple Receiving Antennas:**

Let us consider the transmission of a digital modulated signal *x(t)* over flat slow Rayleigh fading channels using coherent demodulation with *L*th order diversity. The received signal component form the lth diversity channel is

$$r_1(t) = \alpha_1(t)\exp[j\theta_1(t)]x(t) + w_1(t) \quad l = 1,2,....,L$$

It is assumed that (*a*) the channel fading processes are mutually statistically independent, (*b*) the additive white Gaussian noise processes are mutually statistically independent, and (*c*) the channel fading processes and additive noise processes are independent of each other. For a slow fading channel, the complex channel gain can be assumed to be a complex constant over each symbol interval. The demodulator in each channel is optimum for an AWGN channel (e.g., using filters matched to the orthogonal functions $\varphi_n(t), n = 1,2,..., N,$ which define the signal space of the transmitted signal *x(t)*. Therefore, the output of the demodulator of the *l*th branch at the end of the *k*th symbol interval is $\alpha_{lk}\exp(j\theta_{lk})\vec{x}_k + \vec{n}_{lk}$, where $\alpha_{lk}\exp(j\theta_{lk})$ is the complex channel gain of the *l*th channel over the *k*th symbol interval, $\vec{x}_k$ is the vector representation of the transmitted signal over the *k*th symbol interval in the *N*-dimensional signal space and is also the demodulator output for an AWGN channel, and $\vec{n}_{lk} = (n_{lk,1}, n_{lk,2},..., n_{lk,N})$ is the corresponding vector representation of the noise component at the demodulator output due to $w_1(t)$. It can be easily shown that $\|\vec{x}_k\|^2 = E_s$ ($E_s$ is the symbol energy), and each component in $\vec{n}_{lk}$ is a Gaussian random variable with zero mean and variance $N_0/2$ that is independent of any other noise component in the same diversity channel or in a different diversity channel.

Let us consider maximal ratio combining. The decision variable for the *k*th transmitted symbol can be represented by,

$$\begin{aligned}\vec{r}_k &= \sum_{l=1}^{L}[\alpha_{lk}\exp(-j\theta_{lk})][\alpha_{lk}\exp(j\theta_{lk})\vec{x}_k + \vec{n}_{lk}] \\ &= \left[\sum_{l=1}^{L}\alpha_{lk}^2\right]\vec{x}_k + \left[\sum_{l=1}^{L}\alpha_{lk}\exp(-j\theta_{lk})\vec{n}_{lk}\right] \\ &= g_k\vec{x}_k + \vec{n}_k \end{aligned} \tag{2.30}$$

where

$$g_k = \sum_{l=1}^{L}\alpha_{lk}^2$$

and

$$\vec{n}_k = \sum_{l=1}^{L}\alpha_{lk}\exp(-j\theta_{lk})\vec{n}_{lk}$$

For the noise vector, $\vec{n}_k = (n_{k,1}, n_{k,2}, ..., n_{k,N})$, each component is

$$n_{k,n} = \sum_{l=1}^{L}\alpha_{lk}\exp(-j\theta_{lk})n_{lk,n}, n = 1,2,...,N. \tag{2.31}$$

Therefore, given the weighting gain $\alpha_{lk}\exp(-j\theta_{lk}), l = 1,2,...,L,$ each noise component $n_{k,n}$ is a Gaussian random variable with zero mean and variance

$$\sigma_{k,n}^2 = \frac{N_0}{2}\sum_{l=1}^{L}\alpha_{lk}^2 \tag{2.32}$$

For BPSK, $N$=1. The vectors $\vec{r}_k$, $\vec{x}_k$ and $\vec{n}_k$ can be represented by the corresponding scalar variables $r_k$, $x_k$ and $n_k$, respectively. The decision variable for the $k$th transmitted symbol is

$$r_k = g_k x_k + n_k \tag{2.33}$$

where $x_k = \sqrt{E_b}$ for symbol "1" and $x_k = -\sqrt{E_b}$ for symbol "0". The SNR per bit at the output of the combiner for the $k$th symbol is then

$$\gamma_k = \frac{[g_k x_k]^2}{2\sigma_{k,n}^2} = \frac{\left[\sum_{l=1}^{L}\alpha_{lk}^2 x_k\right]^2}{N_0\sum_{l=1}^{L}\alpha_{lk}^2} = \frac{E_b}{N_0}\sum_{l=1}^{L}\alpha_{lk}^2 \tag{2.34}$$

where $\frac{E_b}{N_0}$ is the SNR value for the AWGN channel with $\alpha_{lk} = 1$ and $L$=1. In a Rayleigh fading environment, the $\alpha_{lk}$'s are IID (Independent and Identically Distributed) Rayleigh random variables with parameter $\sigma_\alpha^2$. Therefore $\gamma_k$ follows a chi-square distribution with $2L$ degrees of freedom. Its pdf is given by

$$f_y(x) = \frac{x^{L-1}\exp(-x/\Gamma_c)}{(L-1)!\Gamma_c^L}, x \geq 0, \tag{2.35}$$

where $\Gamma_c = 2\sigma_\alpha^2 E_b / N_0$ is the average SNR per bit in each diversity channel. From equation (2.34), the mean SNR per bit after combining is

$$\Gamma_b = E[\gamma_k] = L\Gamma_c,$$

which increases linearly with *L*. We know that maximal ratio combining indeed gives better performance as the chances for a small instantaneous SNR are further reduced from those with selective diversity, especially with a large *L*. This is because maximal ratio combining makes use of the signal components in all the diversity channels and the mean SNR per bit increases linearly with *L*. However, in selective diversity, at any time, only the signal from the best channel is use for detection. On the other hand, if we compare the two curves with L=2, the difference between them is not significant. From this, we can conclude that, with a low order of diversity reception, selective diversity, equal-gain diversity, and maximal ratio combining diversity achieve similar transmission performance, with the best performance exhibited by maximal ratio combining diversity and the worst performance exhibited by selective diversity.

The analysis of the probability of bit error over a Rayleigh fading channel can be extended to the case with diversity, so that

$$P_b = \int_0^{\infty} P_{e|\gamma}(x) f_y(x) dx. \tag{2.36}$$

where $P_{e|\gamma}(x)$ is the conditional probability of bit error given that the received SNR per bit is $\gamma = x$. We know that for coherent BPSK,

$$P_{e|\gamma}(x) = Q(\sqrt{2x}). \tag{2.37}$$

Substituting Eqs. (2.37) and (2.35) into Eq. (2.36), it can be derived that

$$P_b = [0.5(1-\mu)]^L \sum_{l=0}^{L-1} \binom{L-1+l}{l} [0.5(1+\mu)]^L. \tag{2.38}$$

where

$$\mu = \sqrt{\frac{\Gamma_c}{1+\Gamma_c}}\ .$$

The schematic diagram for an OFDM Broadband Power Line Communication System with multiple receiving antennas is shown below:

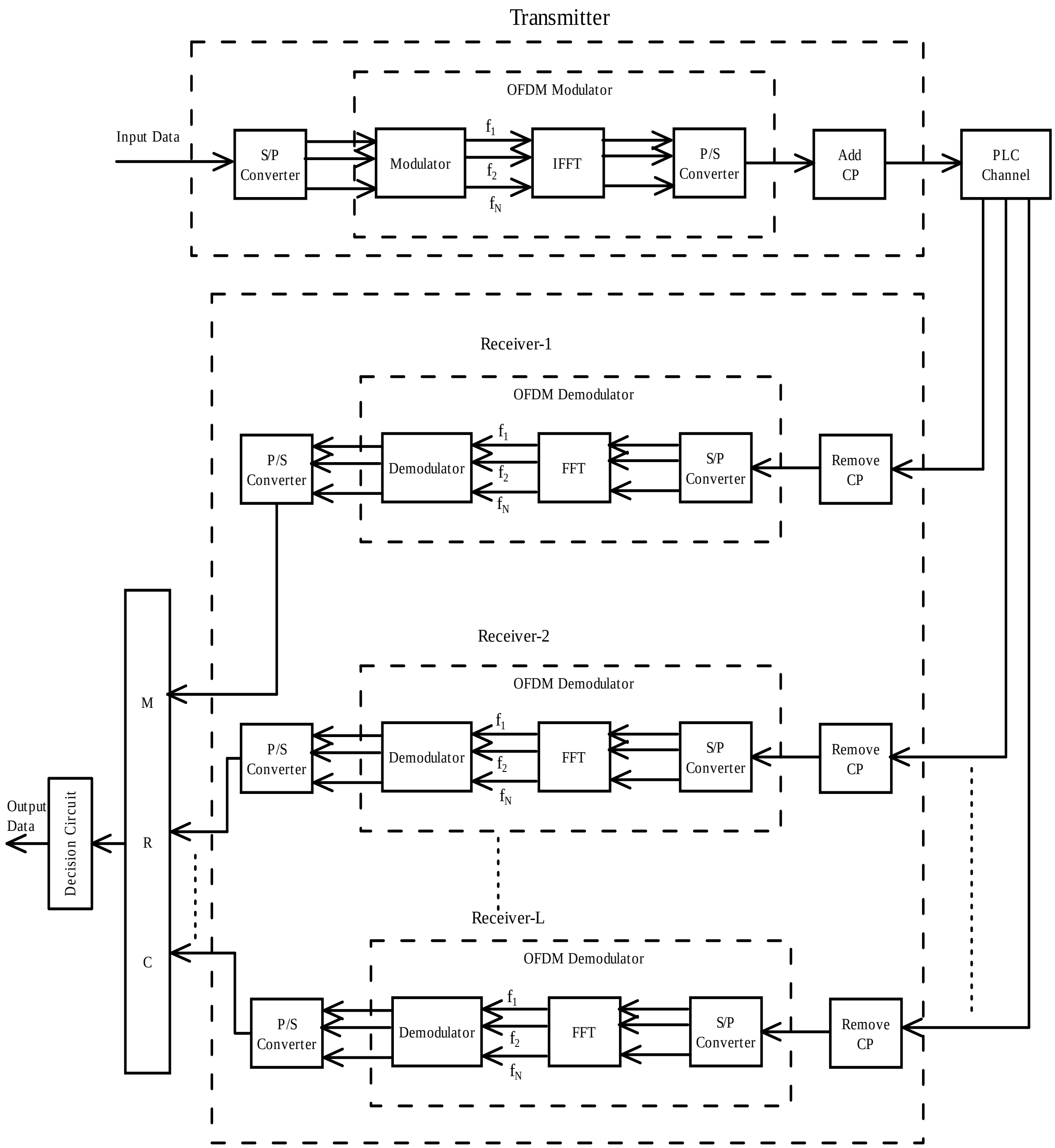


Fig. 2.11: OFDM Broadband Power Line Communication system with multiple receiving antennas

# Chapter 3

## Results and Discussion

Following the theoretical analysis presented in Chapter-2, the bit error rate (BER) performance results of a Broadband Power Line Communication (BPLC) system with OFDM are evaluated for three different channel models. The parameters corresponding to 4-path model, 15-path model and 5-path model are shown in Table 2.2, Table 2.3 and Table 2.4 respectively [10,36]. For the following calculations and discussions, we have also used $T_{guard}$ = 1.28 μs and $T_N$ = 10.24 μs [5] to determine the value of $\alpha_g$ from (2.27) [15].

The results are evaluated for different number of OFDM subcarriers N and are depicted in Fig. 3.1 for 4-path power line channel model. The results are depicted as a function of bit error rate (BER) versus Signal to Noise Ration SNR ($E_b/N_0$) in dB for different values of N i.e. N = 8, 16, 32, 64, 128, 256 etc. It is evident from the results that there are improvements in BER performance with increase in the number of OFDM subcarrier.

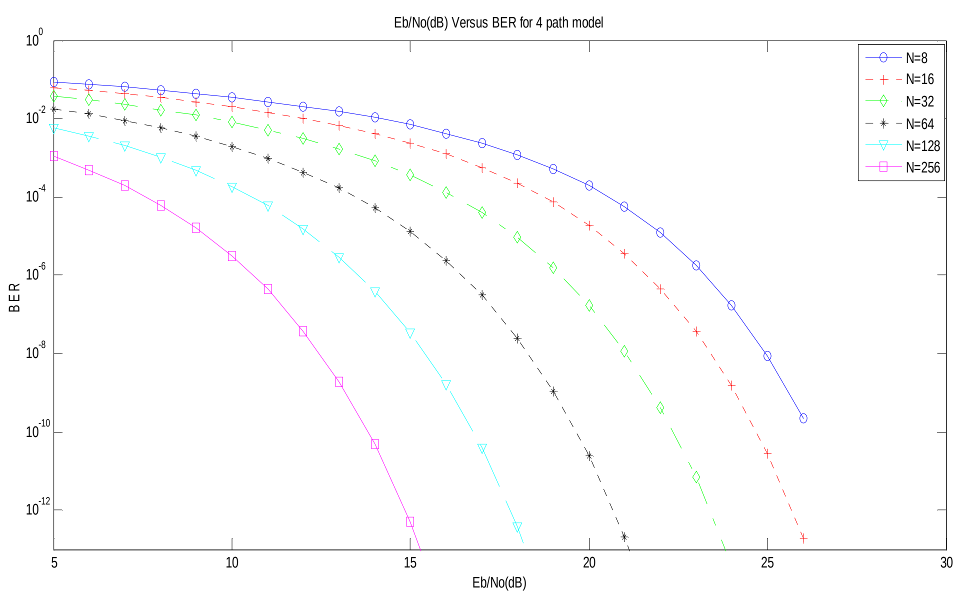


Fig. 3.1: BER vs. SNR ($E_b/N_0$) in dB for OFDM BPLC system with single receiver for 4-path model

Further, the plots of bit error rate (BER) versus SNR ($E_b/N_0$) for 15-path channel model are shown in Fig. 3.2 with number of subcarrier as a parameter. It is noticed that there is improvement in BER performance with increase in the number of subcarriers.

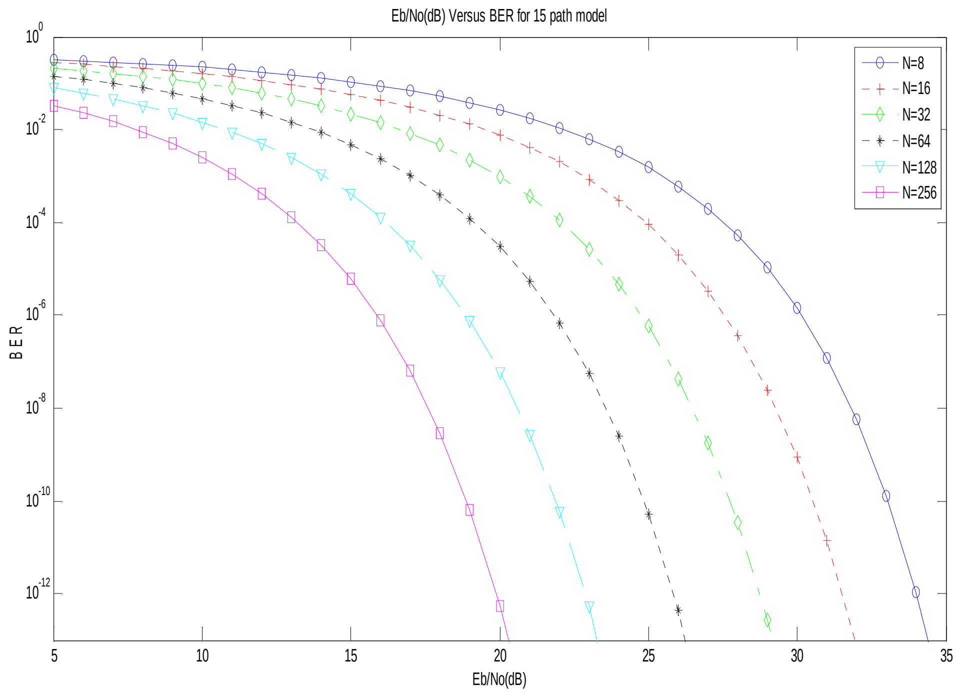


Fig. 3.2: BER vs. SNR ($E_b/N_0$) in dB for OFDM BPLC system with single receiver for 15-path model

For 5-path model, the attenuation parameters $a_0$, $a_1$ and k are considered as variable whether they are constant in case of 4-path model and 15-path model. The plots of BER versus SNR ($E_b/N_0$) for 5-path channel model are shown in Fig. 3.3 with number of subcarrier N as a parameter. It is noticed also that there is improvement in BER performance with increase in the number of subcarriers.

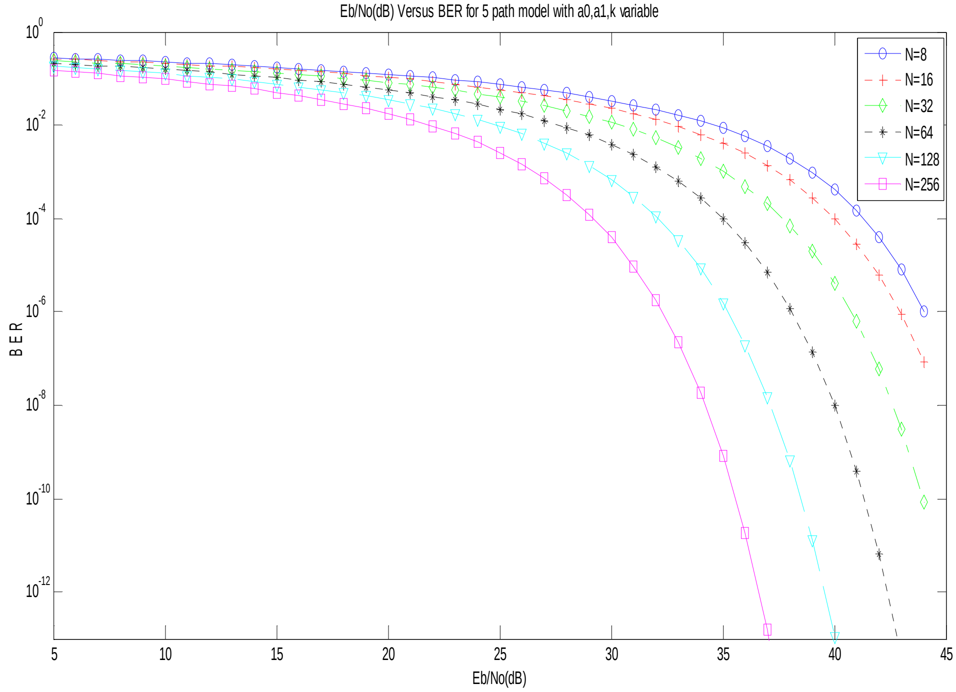


Fig. 3.3: BER vs. SNR ($E_b/N_0$) in dB for OFDM BPLC system with single receiver for 5-path model with $a_0$, $a_1$, k variable

The receiver sensitivity to achieve a given BER of $10^{-6}$ is shown in Table 3.1, Table 3.2 and Table 3.3 for 4-path model, 15-path model and 5-path models respectively which have been determined from Fig. 3.1, Fig. 3.2 and Fig. 3.3 respectively.

Table 3.1: Values of $E_b/N_0$ and N with BER=$10^{-6}$ for 4-path model

| N | $E_b/N_0$ (dB) |
|---|---|
| 8 | 23.17 |
| 16 | 21.71 |
| 32 | 19.39 |
| 64 | 16.65 |
| 128 | 13.6 |
| 256 | 10.49 |

Table 3.2: Values of $E_b/N_0$ and N with BER=$10^{-6}$ for 15-path model

| N | Eb/N0 (dB) |
|---|---|
| 8 | 30.22 |
| 16 | 27.5 |
| 32 | 24.85 |
| 64 | 21.91 |
| 128 | 18.97 |
| 256 | 15.88 |

Table 3.3: Values of $E_b/N_0$ and N with BER=$10^{-6}$ for 5-path model

| N | Eb/N0 (dB) |
|---|---|
| 8 | 43.91 |
| 16 | 43.13 |
| 32 | 41.09 |
| 64 | 38.44 |
| 128 | 35.31 |
| 256 | 32.19 |

The plots of receiver sensitivity versus SNR ($E_b/N_0$) are depicted in Fig. 3.4 for all 3 channel models together. It is noticed that there are significant variation in the values of receiver sensitivity between the three models. For example, the required receiver sensitivity for N=64 for 4-path model is 16.65, for 15-path model is 21.91 dB and for 5-path model is 38.44 dB. So the improvement for N=64 is almost 5.26 dB for 4-path model with respect to 15-path model and the improvement is approximate 21.79 dB with respect to 5-path model. So, it is clear that 4-path model estimates better system performance than the other 2 models.

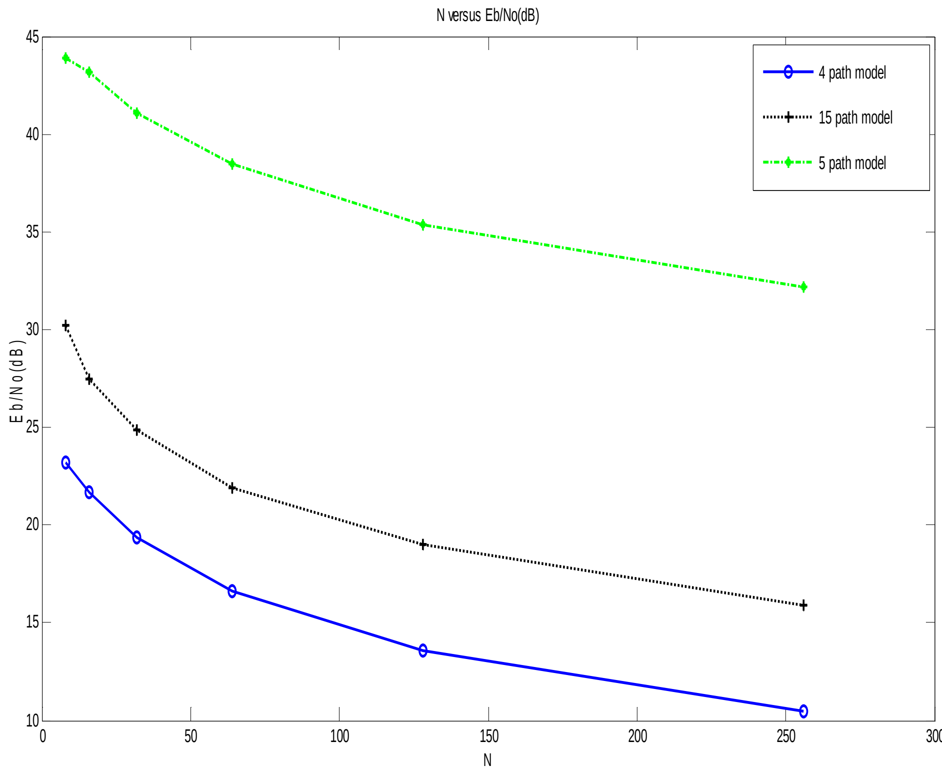


Fig. 3.4: Number of OFDM subcarriers N versus SNR ($E_b/N_0$) in dB for BER=$10^{-6}$

**OFDM BPLC System with Multiple Receiving Antennas:**

4-path model:

Using multiple power line receiving ports, the results are evaluated following the analysis given in section 2.7. The bit error rate performance results are depicted in Fig. 3.5 through Fig. 3.10 considering the 4-path channel model as a function of Signal to Noise Ratio (SNR) for 8 number of OFDM subcarriers (N=8, 16, 32, 64, 128 & 256) and number of receivers L as a parameter (L=1-8). It is noticed that the BER performance improves with increase in the number of receiver ports. Comparison of Fig. 3.5 to Fig. 3.10 reveals that there are improvement in system performance with increase in the number of OFDM subcarriers N.

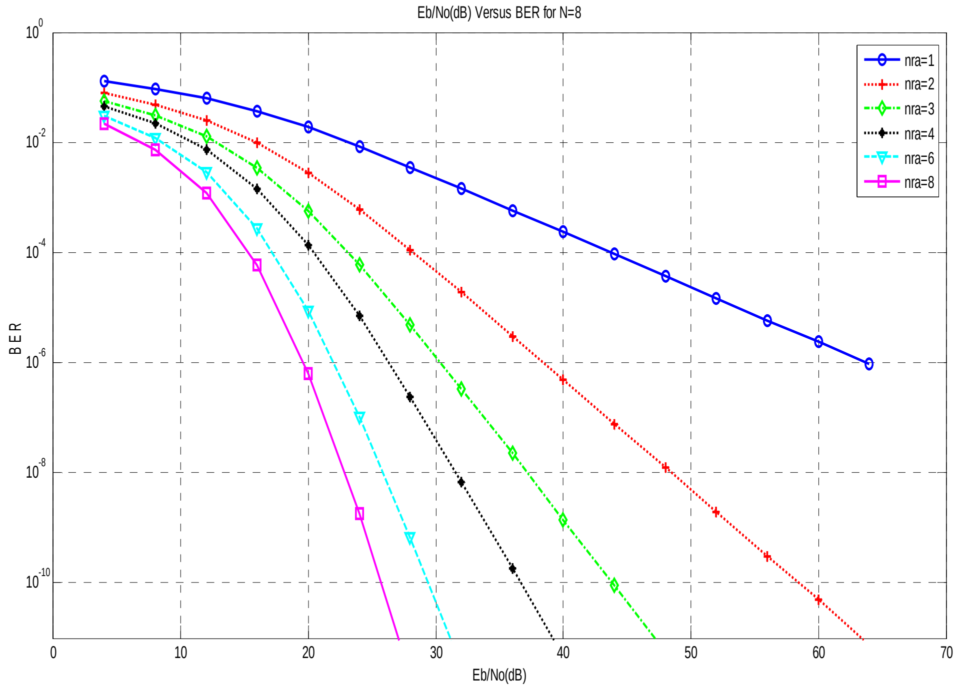


Fig. 3.5: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=8 based on 4-path channel model

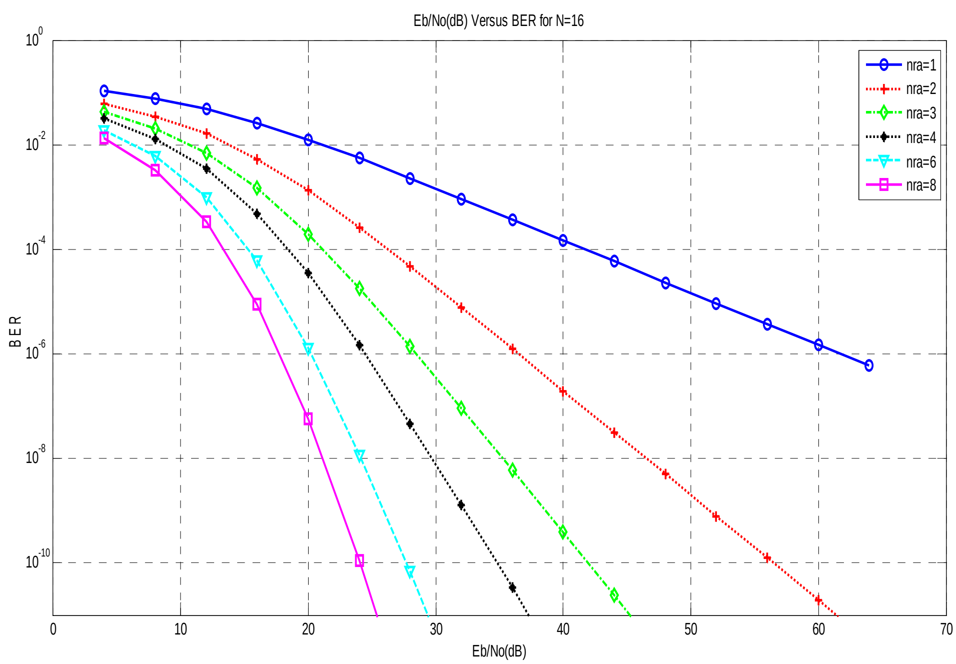


Fig. 3.6: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=16 based on 4-path channel model

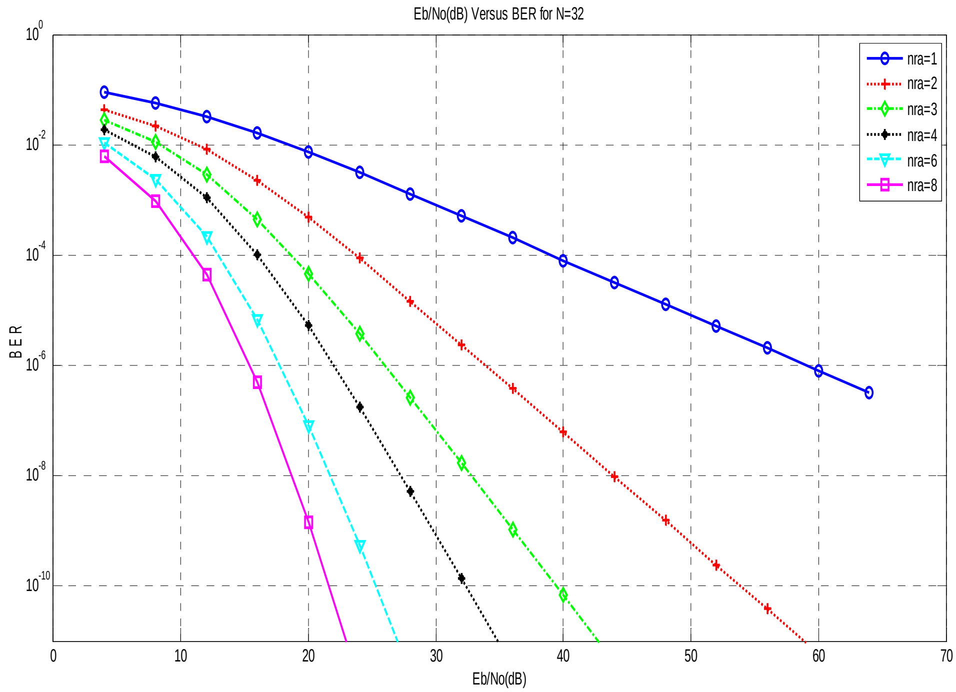


Fig. 3.7: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=32 based on 4-path channel model

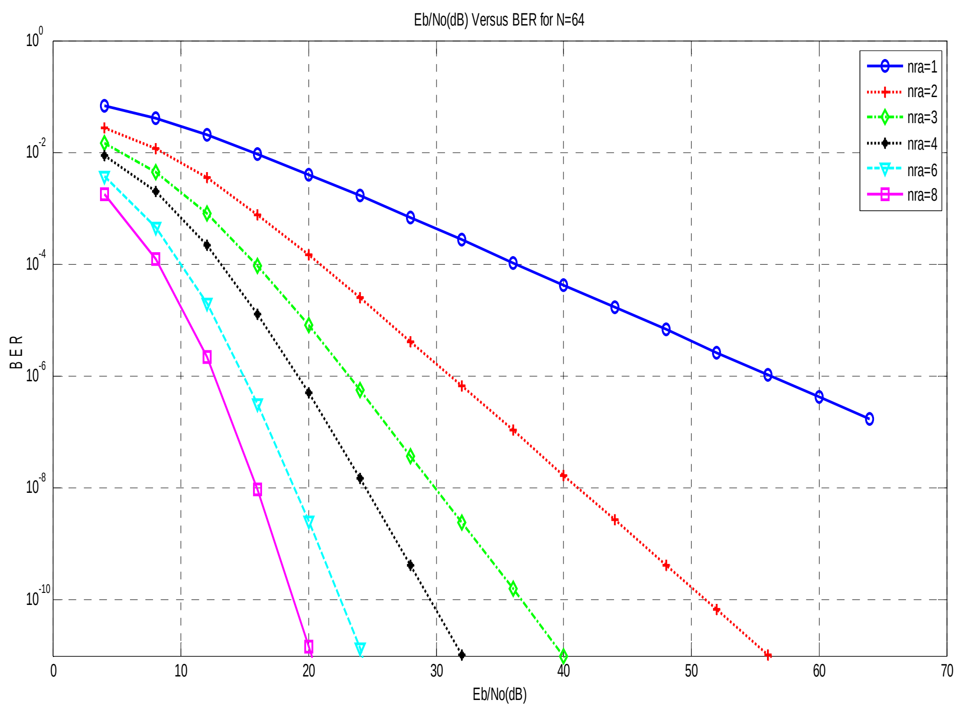


Fig. 3.8: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=64 based on 4-path channel model

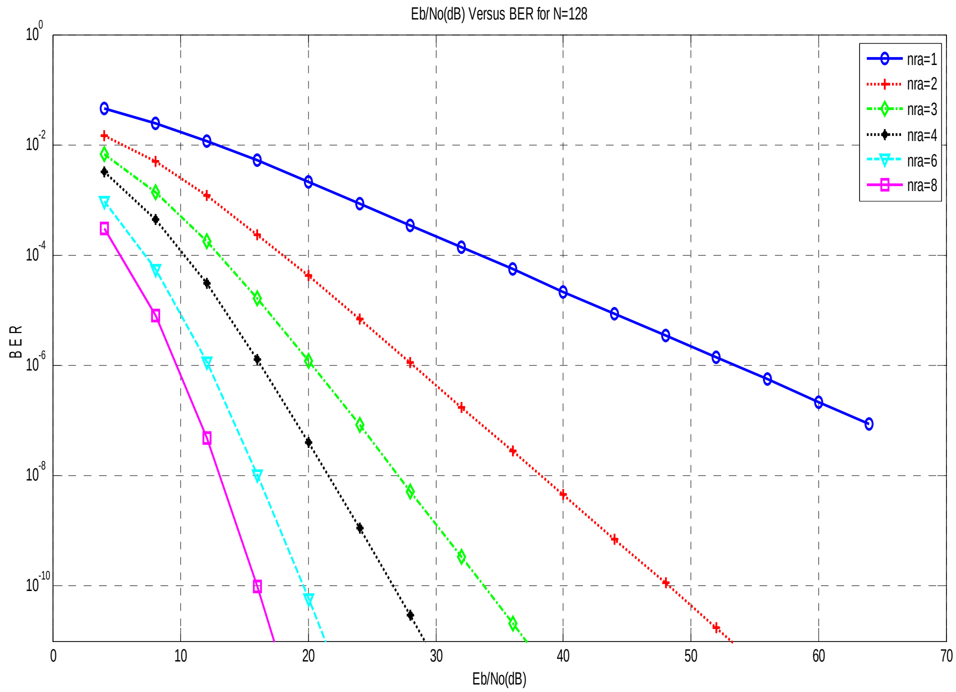


Fig. 3.9: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=128 based on 4-path channel model

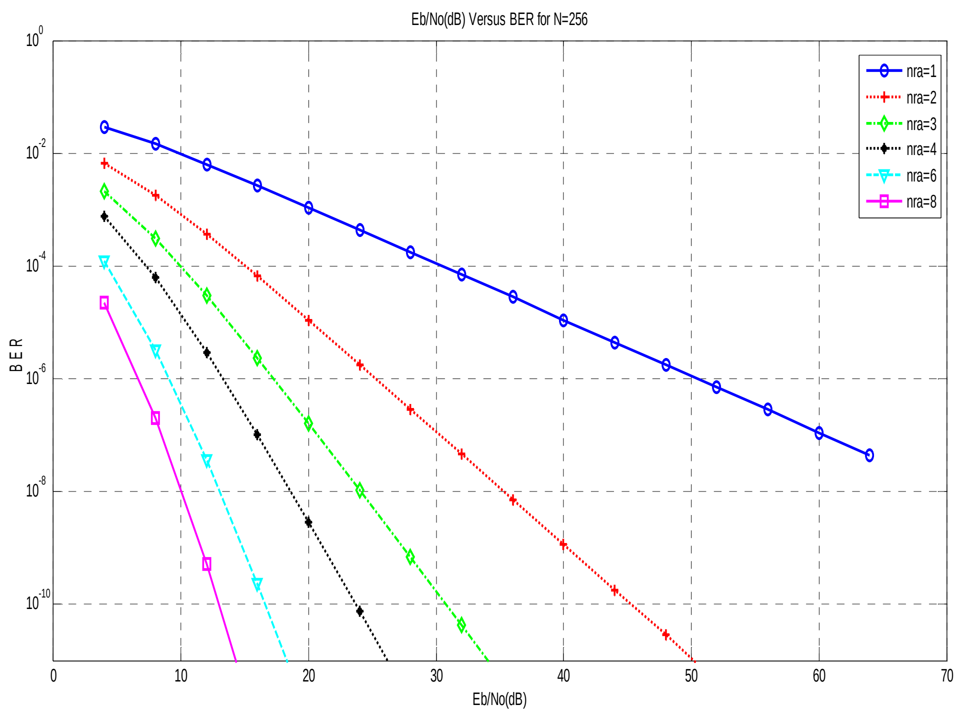


Fig. 3.10: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=256 based on 4-path channel model

**15-path model:**

Fig. 3.11 through Fig. 3.16 shows the similar results of BER versus SNR for 15-path channel model with number of receiver (L) as a parameter.

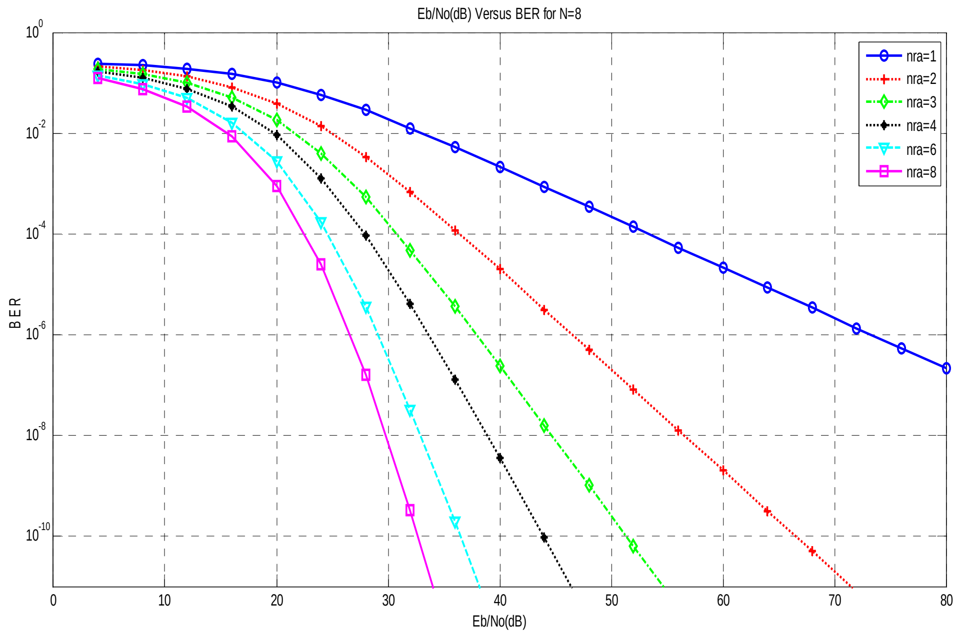


Fig. 3.11: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=8 based on 15-path channel model

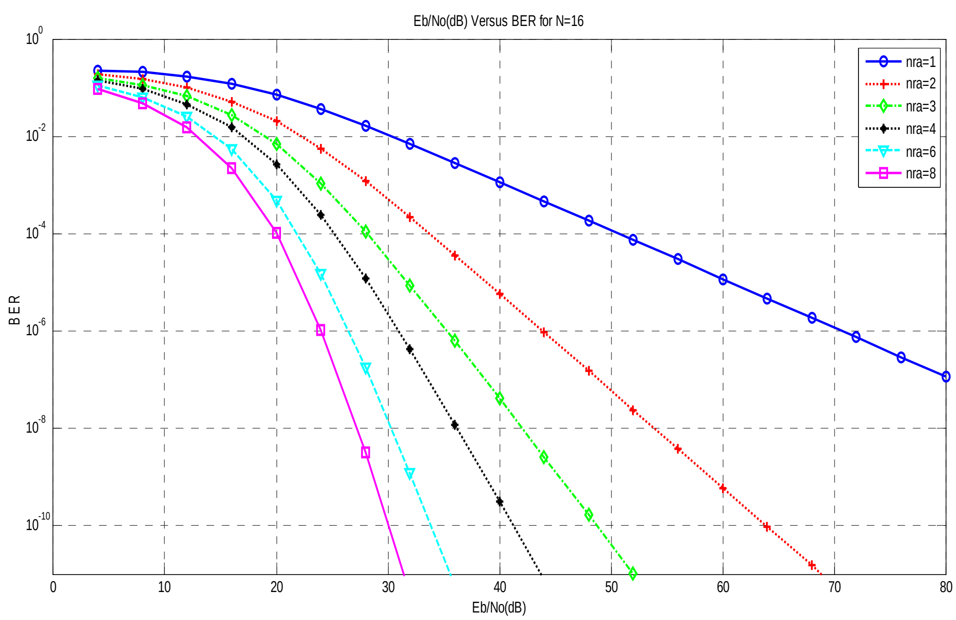


Fig. 3.12: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=16 based on 15-path channel model

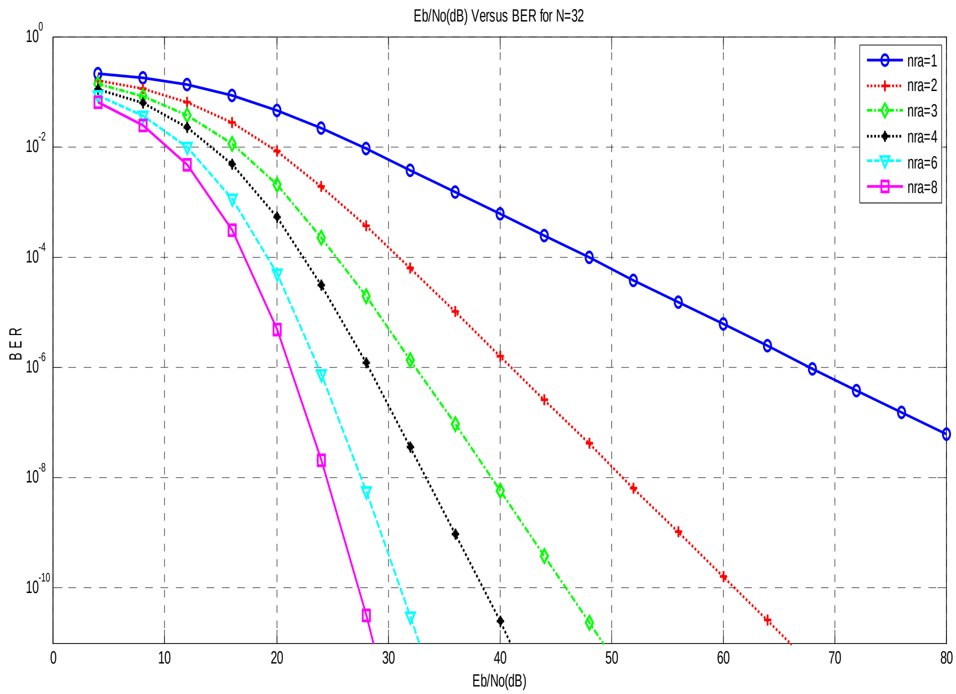


Fig. 3.13: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=16 based on 15-path channel model

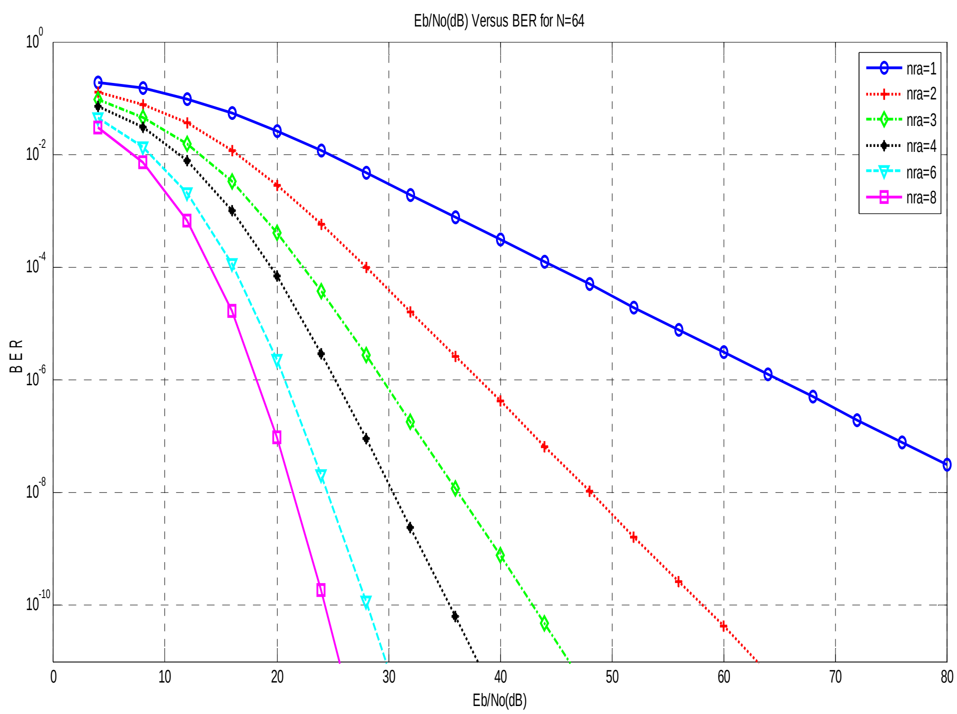


Fig. 3.14: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=64 based on 15-path channel model

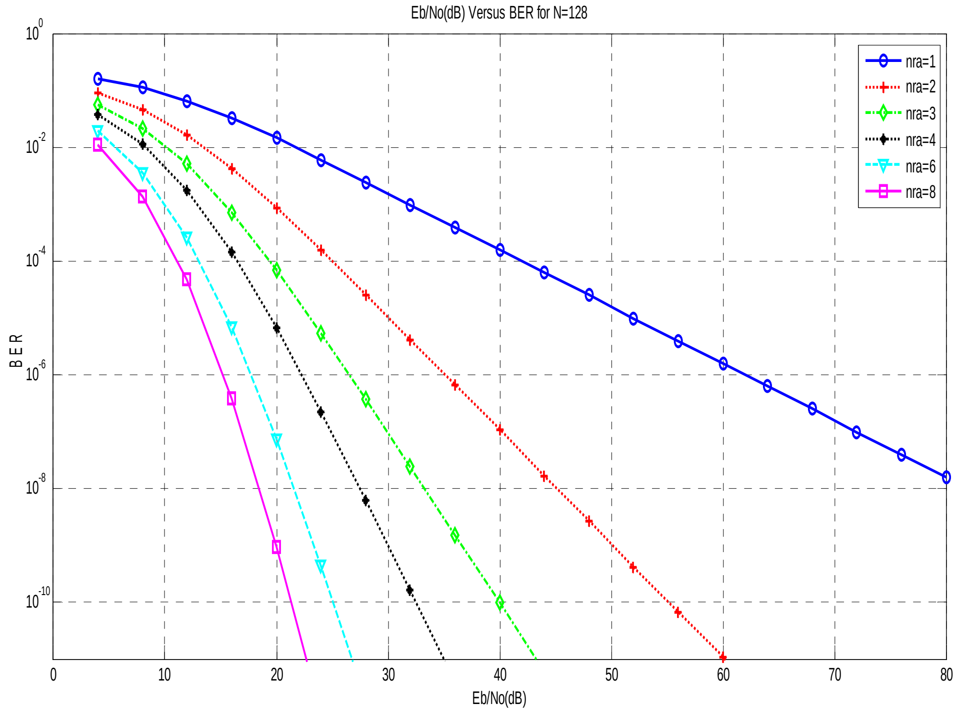


Fig. 3.15: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=128 based on 15-path channel model

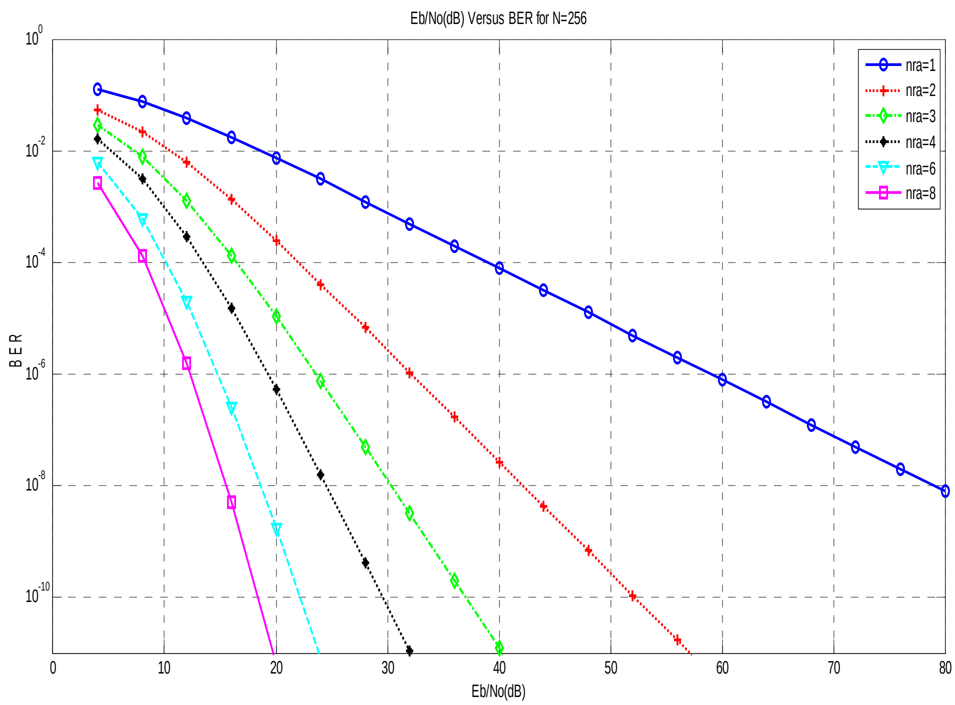


Fig. 3.16: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=256 based on 15-path channel model

**5-path model:**

For 5-path model, similar results are also evaluated and are shown in Fig. 3.17 through Fig. 3.22.

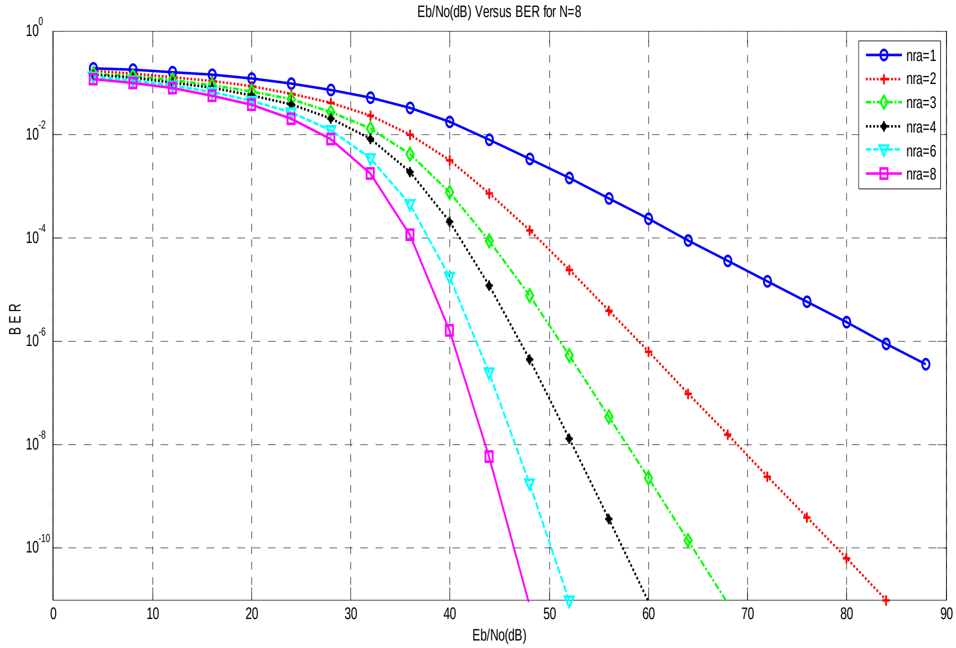


Fig. 3.17: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=8 based on 5-path channel model

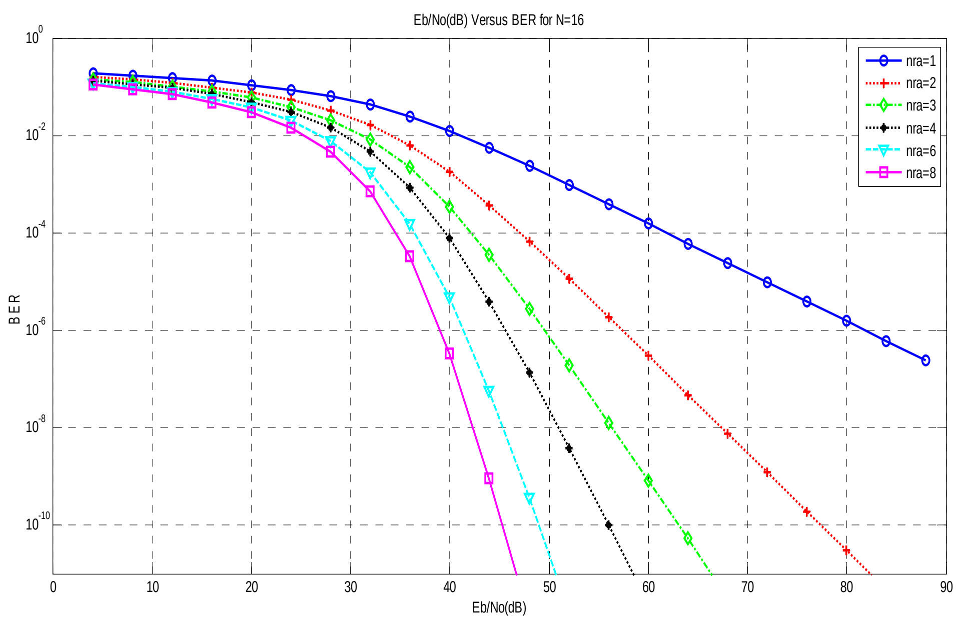


Fig. 3.18: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=16 based on 5-path channel model

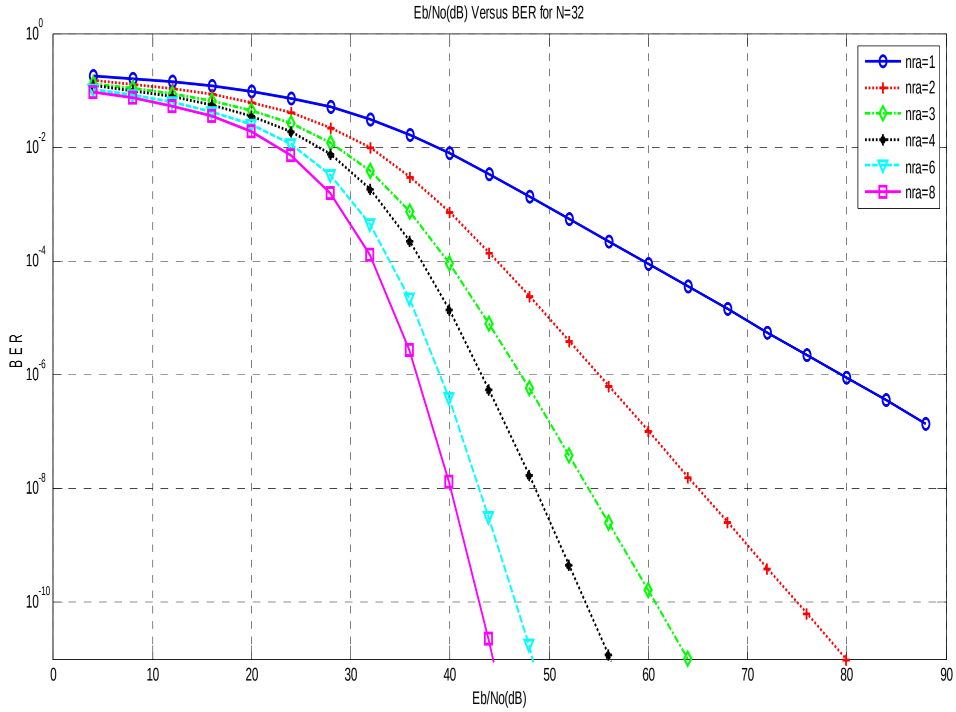


Fig. 3.19: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=32 based on 5-path channel model

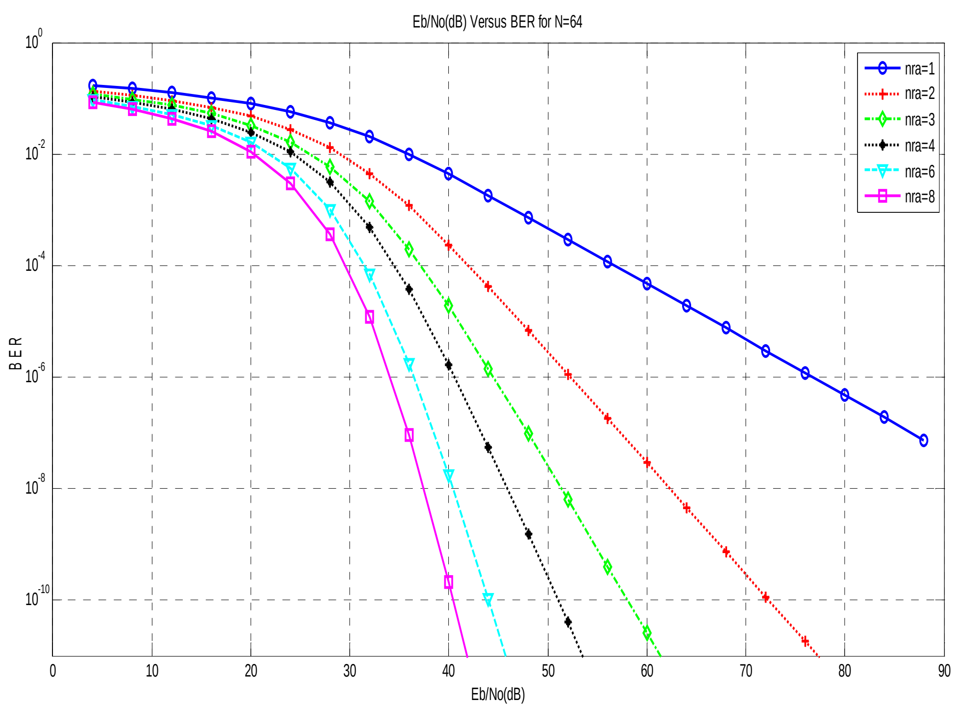


Fig. 3.20: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=64 based on 5-path channel model

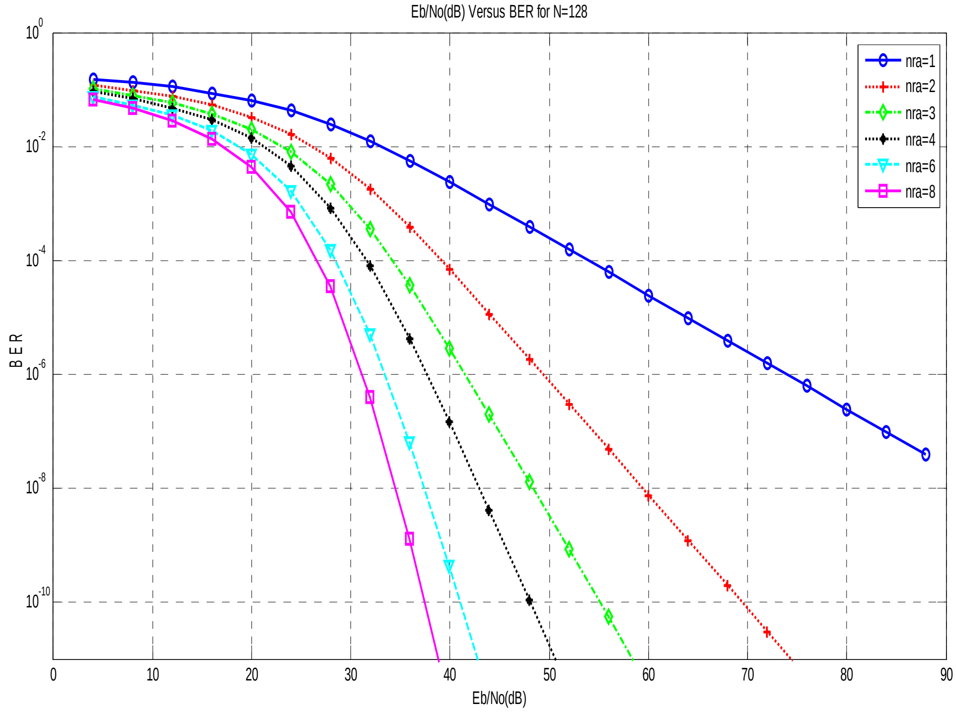


Fig. 3.21: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=128 based on 5-path channel model

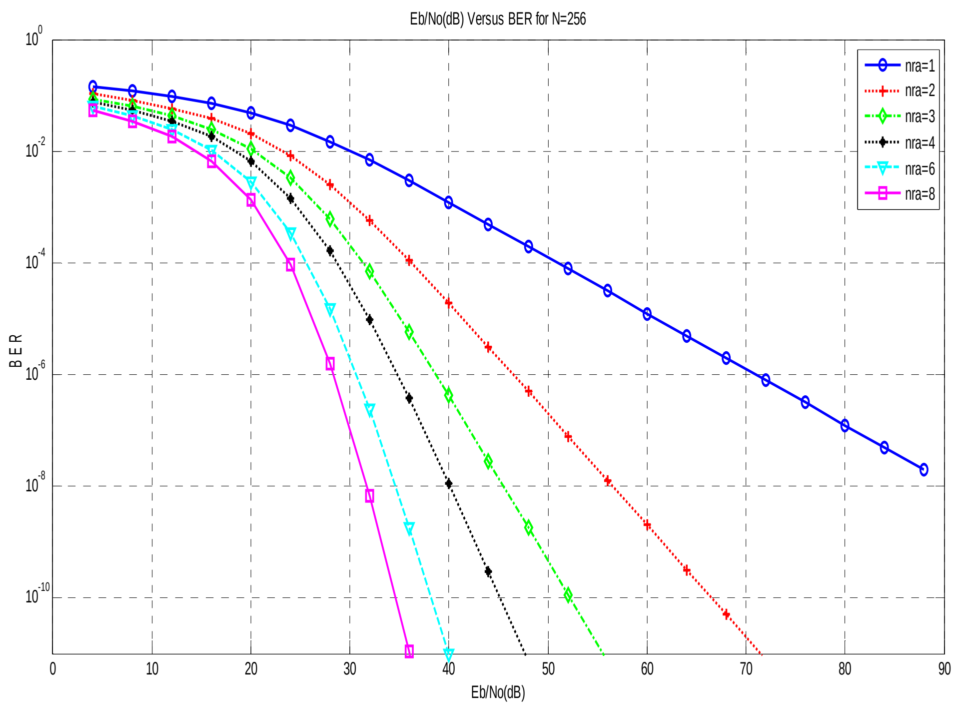


Fig. 3.22: Plots of Bit Error Rate (BER) versus SNR ($E_b/N_0$) in dB for an OFDM BPLC system with number of OFDM subcarrier N=256 based on 5-path channel model

**Receiving Sensitivity:**

Comparison of the various plots reveal that there are improvement in BER performance with increase in the number of OFDM subcarrier. The required receiver sensitivity to attain BER=$10^{-6}$ are determined from the curves Fig. 3.5 through Fig. 3.22 and are listed in the following Table 3.4, Table 3.5 and Table 3.6 for 4-path model, 15-path model and 5-path model respectively.

Table 3.4: Values of $E_b/N_0$ (dB) with respect to number of receivers L for 4-path model

| Number of Receiving Antennas L | $E_b/N_0$ (dB) For N=8 | $E_b/N_0$ (dB) For N=16 | $E_b/N_0$ (dB) For N=32 | $E_b/N_0$ (dB) For N=64 | $E_b/N_0$ (dB) For N=128 | $E_b/N_0$ (dB) For N=256 |
|---|---|---|---|---|---|---|
| 1 | 63.93 | 61.79 | 59.28 | 56.43 | 53.57 | 50.36 |
| 2 | 38.57 | 36.43 | 33.93 | 31.43 | 28.21 | 25.18 |
| 3 | 30.36 | 28.57 | 26.21 | 23.21 | 20.21 | 17.32 |
| 4 | 26.43 | 24.64 | 22.14 | 19.29 | 16.43 | 13.57 |
| 6 | 21.96 | 20.18 | 17.86 | 15.54 | 12.5 | 9.29 |
| 8 | 19.42 | 17.86 | 15.36 | 12.86 | 9.64 | 6.79 |

Table 3.5: Values of $E_b/N_0$ (dB) with respect to number of receivers L for 15-path model

| Number of Receiving Antennas L | $E_b/N_0$ (dB) For N=8 | $E_b/N_0$ (dB) For N=16 | $E_b/N_0$ (dB) For N=32 | $E_b/N_0$ (dB) For N=64 | $E_b/N_0$ (dB) For N=128 | $E_b/N_0$ (dB) For N=256 |
|---|---|---|---|---|---|---|
| 1 | 73.25 | 70.75 | 68 | 65 | 61.75 | 59 |
| 2 | 46.25 | 44 | 41.25 | 38 | 35.25 | 32.25 |
| 3 | 38 | 35 | 32.5 | 29.5 | 26.5 | 23.5 |
| 4 | 33.75 | 31 | 28 | 25.25 | 22.5 | 19 |
| 6 | 29 | 26.5 | 23.75 | 20.75 | 17.75 | 14.75 |
| 8 | 26.5 | 24.25 | 21 | 18 | 15.25 | 12.75 |

Table 3.6: Values of $E_b/N_0$ (dB) with respect to number of receivers L for 5-path model

| Number of Receiving Antennas L | $E_b/N_0$ (dB) For N=8 | $E_b/N_0$ (dB) For N=16 | $E_b/N_0$ (dB) For N=32 | $E_b/N_0$ (dB) For N=64 | $E_b/N_0$ (dB) For N=128 | $E_b/N_0$ (dB) For N=256 |
|---|---|---|---|---|---|---|
| 1 | 83.86 | 81.82 | 79.36 | 76.82 | 74.1 | 71 |
| 2 | 59.09 | 57.27 | 54.82 | 52.27 | 49.36 | 46.55 |
| 3 | 51.14 | 49.54 | 47.27 | 44.55 | 41.55 | 39 |
| 4 | 47.27 | 45.68 | 43.63 | 40.45 | 37.73 | 35 |
| 6 | 43.18 | 41.82 | 39.09 | 36.64 | 33.64 | 30.91 |
| 8 | 40.45 | 39.09 | 36.82 | 34.27 | 31.1 | 28.36 |

The plots of receiver sensitivity are then depicted in the following Fig. 3.23, Fig. 3.24 and Fig. 3.25 for 4-path, 15-path and 5-path channel models respectively from the values of aforementioned Table 3.4, 3.5 and 3.6 as a function of number of receivers (L) with number of OFDM subcarrier as parameter. It is noticed that there is significant improvement in receiver sensitivity with increase in number of receiver at a given value of OFDM subcarrier N for a particular BER=$10^{-6}$. There are further improvements with increase in the number of subcarriers.

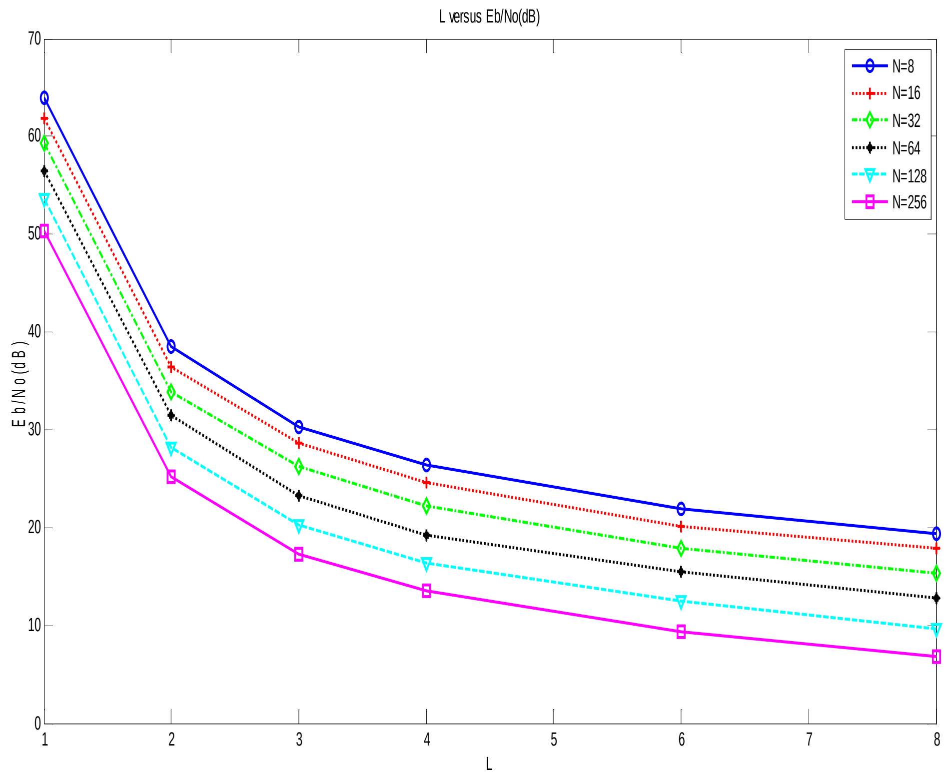


Fig. 3.23: Number of receivers (L) versus SNR ($E_b/N_0$) in dB for 4-path model

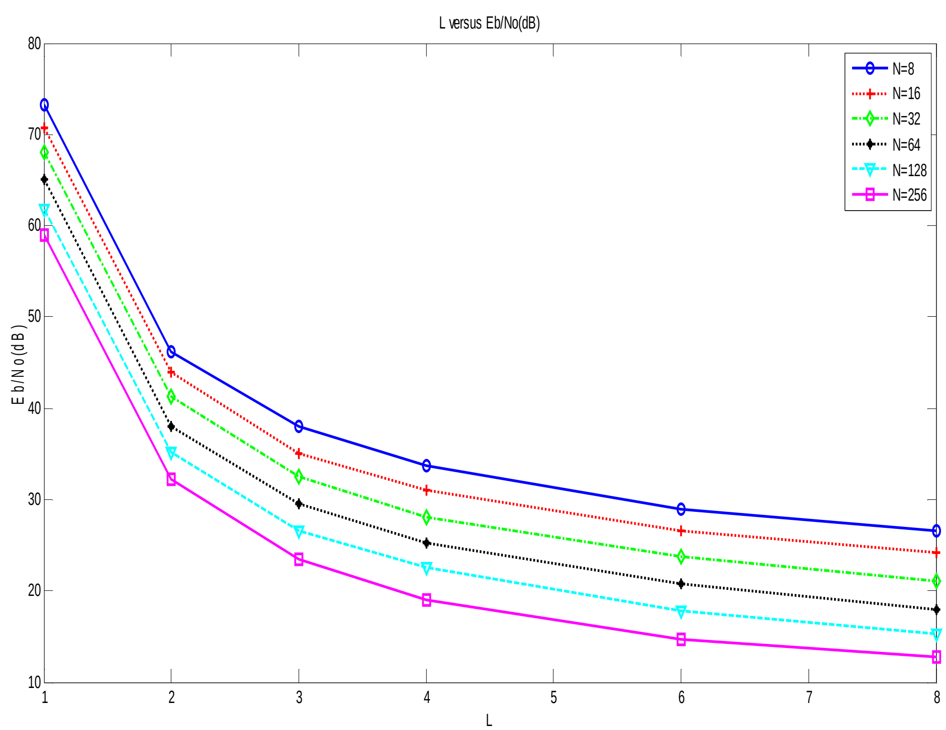


Fig. 3.24: Number of receivers (L) versus SNR ($E_b/N_0$) in dB for 15-path model

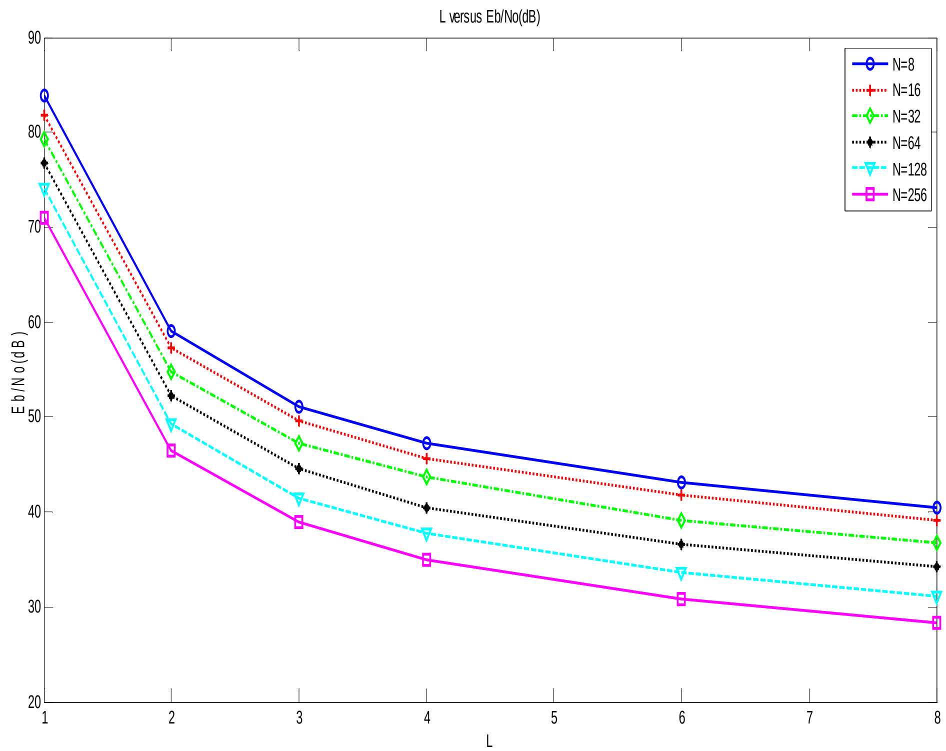


Fig 3.25: Number of receivers (L) versus SNR ($E_b/N_0$) in dB for 5-path model

**Receiving Sensitivity Improvement:**

The required receiver sensitivity improvement with a particular BER=$10^{-6}$ are listed in the following Table 3.7, Table 3.8 and Table 3.9 for 4-path model, 15-path model and 5-path model respectively. The plots of improvement in receiver sensitivity are then depicted in Fig. 3.26, Fig. 3.27 and Fig. 3.28 as a function of receiver number corresponding to 4-path, 15-path and 5-path models with number of subcarrier as a parameter. We have used the reference value as 63.93 dB, 73.25 dB and 83.86 dB for 4-path, 15-path and 5-path model respectively.

Table 3.7: Change in $E_b/N_0$ (dB) with respect to number of receivers L for 4-path model

| Number of Receiving Antennas L | Change in $E_b/N_0$ (dB) For N=8 | Change in $E_b/N_0$ (dB) For N=16 | Change in $E_b/N_0$ (dB) For N=32 | Change in $E_b/N_0$ (dB) For N=64 | Change in $E_b/N_0$ (dB) For N=128 | Change in $E_b/N_0$ (dB) For N=256 |
|---|---|---|---|---|---|---|
| 1 | 0 | 2.14 | 4.65 | 7.5 | 10.36 | 13.57 |
| 2 | 25.36 | 27.5 | 30 | 32.5 | 35.72 | 38.75 |
| 3 | 33.57 | 35.36 | 37.72 | 40.72 | 43.72 | 46.61 |
| 4 | 37.5 | 39.29 | 41.79 | 44.64 | 47.5 | 50.36 |
| 6 | 41.97 | 43.75 | 46.07 | 48.39 | 51.43 | 54.64 |
| 8 | 44.51 | 46.07 | 48.57 | 51.07 | 54.29 | 57.14 |

Table 3.8: Change in $E_b/N_0$ (dB) with respect to number of receivers L for 15-path model

| Number of Receiving Antennas L | $E_b/N_0$ (dB) For N=8 | $E_b/N_0$ (dB) For N=16 | $E_b/N_0$ (dB) For N=32 | $E_b/N_0$ (dB) For N=64 | $E_b/N_0$ (dB) For N=128 | $E_b/N_0$ (dB) For N=256 |
|---|---|---|---|---|---|---|
| 1 | 0 | 2.5 | 5.25 | 8.25 | 11.5 | 14.25 |
| 2 | 27 | 29.25 | 32 | 35.25 | 38 | 41 |
| 3 | 35.25 | 38.25 | 40.75 | 43.75 | 46.75 | 49.75 |
| 4 | 39.5 | 42.25 | 45.25 | 48 | 50.75 | 54.25 |
| 6 | 44.25 | 46.75 | 49.5 | 52.5 | 55.5 | 58.5 |
| 8 | 46.75 | 49 | 52.25 | 55.25 | 58 | 60.5 |

Table 3.9: Change in $E_b/N_0$ (dB) with respect to number of receivers L for 5-path model

| Number of Receiving Antennas L | $E_b/N_0$ (dB) For N=8 | $E_b/N_0$ (dB) For N=16 | $E_b/N_0$ (dB) For N=32 | $E_b/N_0$ (dB) For N=64 | $E_b/N_0$ (dB) For N=128 | $E_b/N_0$ (dB) For N=256 |
|---|---|---|---|---|---|---|
| 1 | 0 | 2.04 | 4.5 | 7.04 | 9.76 | 12.86 |
| 2 | 24.77 | 26.59 | 29.04 | 31.59 | 34.5 | 37.31 |
| 3 | 32.72 | 34.32 | 36.59 | 39.31 | 42.31 | 44.86 |
| 4 | 36.59 | 38.18 | 40.23 | 43.41 | 46.13 | 48.86 |
| 6 | 40.68 | 42.04 | 44.77 | 47.22 | 50.22 | 52.95 |
| 8 | 43.41 | 44.77 | 47.04 | 49.59 | 52.76 | 55.5 |

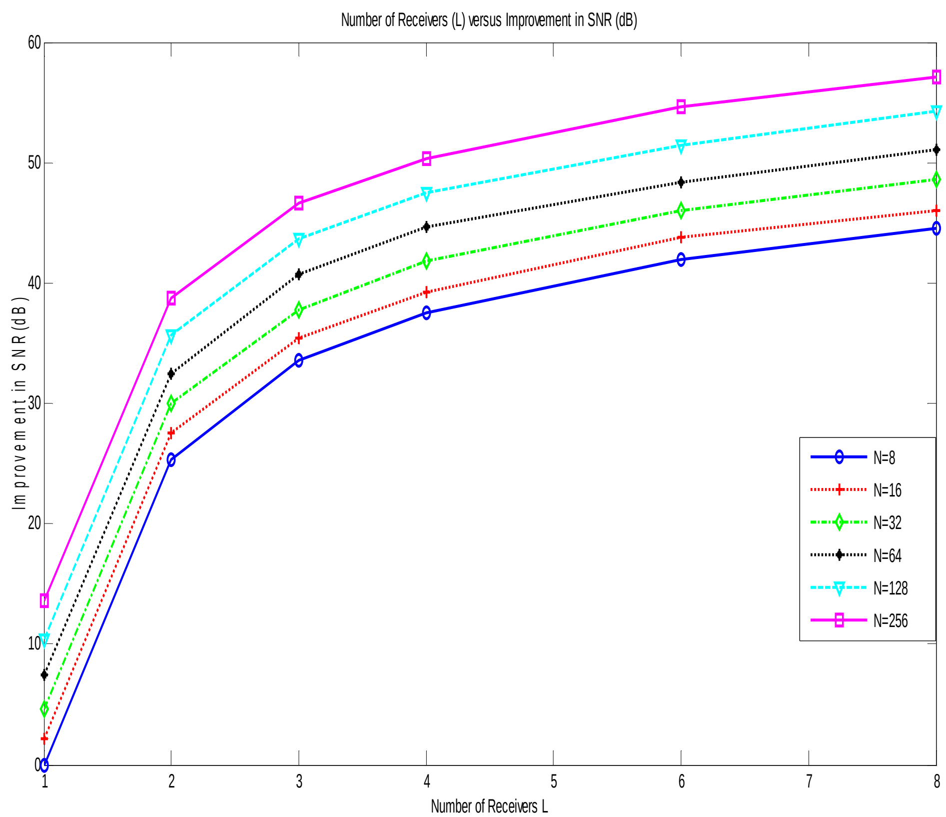


Fig. 3.26: Number of receivers (L) versus improvement in SNR (dB) for 4-path model

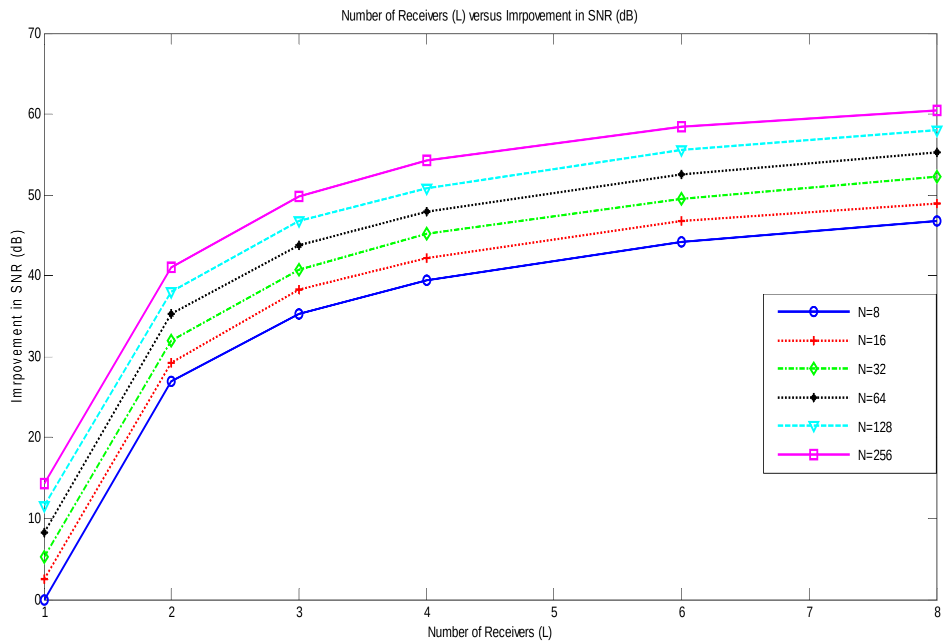


Fig. 3.27: Number of receivers (L) versus improvement in SNR (dB) for 15-path model

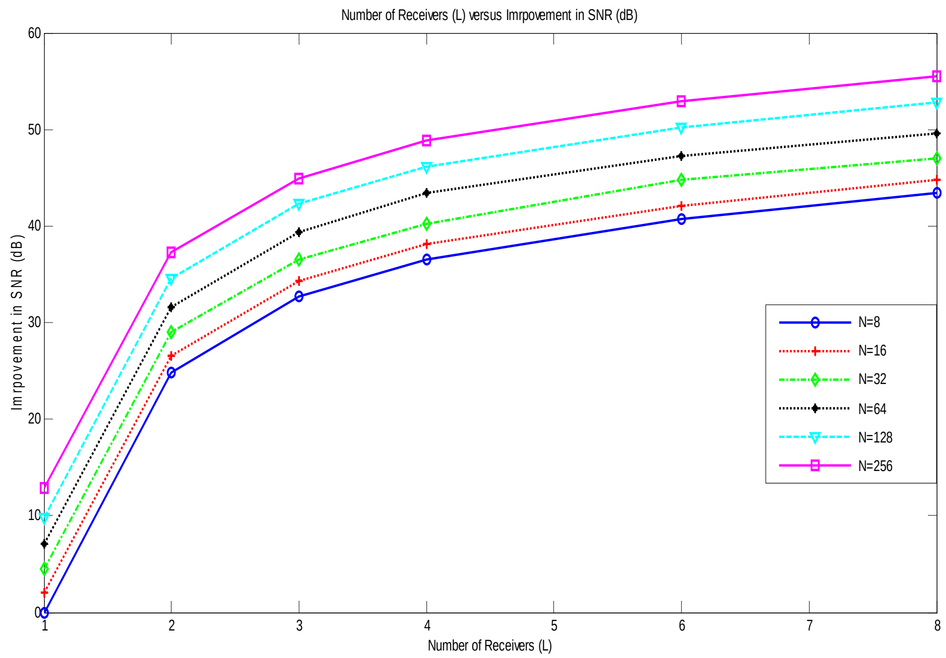


Fig. 3.28: Number of receivers (L) versus improvement in SNR (dB) for 5-path model

It is noticed that improvement is significant and of the order of 10 dB to 55 dB depending on the number of OFDM subcarriers.

In [58], a comparison between CDMA and OFDM systems for Broadband Power Line Communication (BPLC) system is conducted. The authors of [58] have taken into account both multipath and impulsive response effect. Number of multipath in this case was 4. The comparison result according to [58] is given below in Fig. 3.29. We have compared this result with the plot BER versus SNR in dB for an OFDM BPLC system with number of OFDM subcarriers N=32 for the 4-path channel model shown in Fig. 3.7.

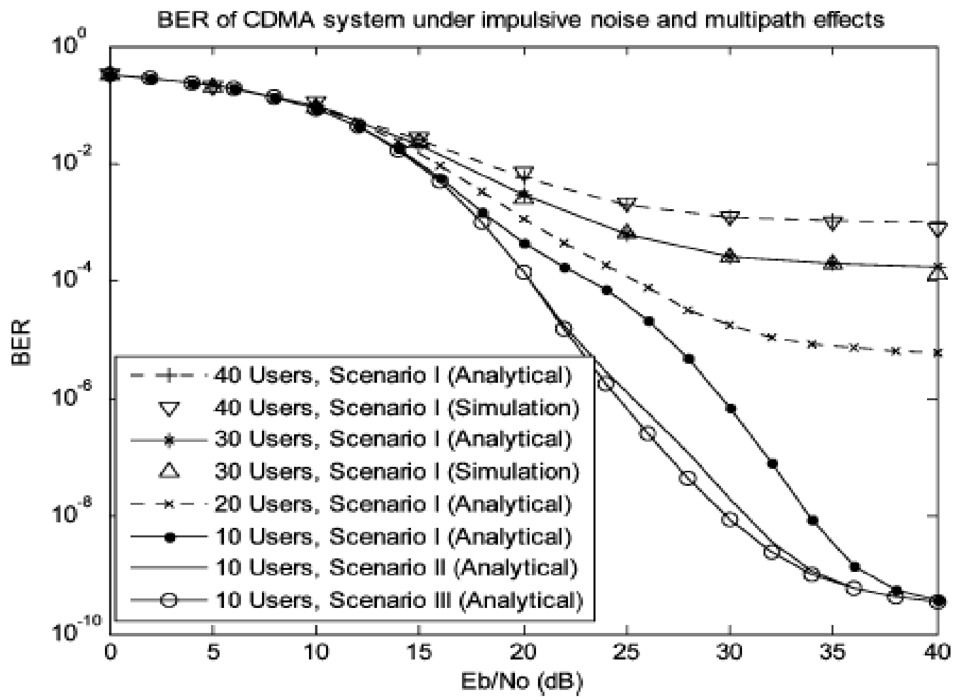


Fig. 3.29: BER of RAKE receiver CDMA system under the impulsive noise and multipath effects [58]

It is noticed that the results are almost similar. The performance in Fig. 3.29 is improved further with the decrease in number of CDMA users whether in our case the BER performance is improved further with the increase in number of OFDM subcarrier N and number of receivers L.

So, in conclusion we can say that the analytical and simulation results above have verified the accuracy of the analytical model of our OFDM BPLC system with multiple receivers.

# Chapter 4

## Conclusion

Power line networks are an excellent infrastructure for broadband communication, though there exists some technical difficulties as noise, attenuation, multipath scenario etc. are presented in power line system as power lines are not specifically designed for data communication purposes. OFDM modulation is an attractive way to mitigate the limitations of power line system for communication purposes. In this thesis work, an analytical model of multipath propagation due to reflection for different branches of a power line network is considered for a given number of branches and load impedance. The analysis is carried out for a broadband power line communication system (BPLC) to evaluate the bit error rate (BER) with different channel models e.g. 4-path model, 15-path model and 5-path model. The results are evaluated for different number of OFDM subcarriers and different channel parameters. The analytical expression of the signal at the receiving end is then developed considering multicarrier modulation using OFDM. The analysis is further extended with multiple receiving antennas to find the expression of the output of the combiner considering Maximal ratio Receiver Combining (MRRC) scheme. The bit error rate is evaluated following standard BER expression for OFDM carriers. The computations of BER are carried out for different multipath propagation models and different power line branches and load impedance values and channel transfer function.

The theoretical analysis of the BER performance of an OFDM based PLC system with and without fading, with different noise models and multipath propagation have been reviewed in Chapter 2. Multipath model for the powerline channel proposed by Zimmerman-Dostert is considered. Expression of SNR from BER is also presented in Chapter 2. Finally, theoretical analyses are provided without and with receive diversity considering MRC (maximal ratio combining) scheme.

Following the theoretical analysis presented in Chapter-2, the performance results are evaluated for different number of OFDM subcarriers N and are depicted as a function of bit error rate (BER) versus Signal to Noise Ration SNR ($E_b/N_0$) in dB for different values of N i.e. N = 8, 16, 32, 64, 128, 256 etc. It is evident from the results that there are improvements in BER performance with increase in the number of OFDM subcarrier for all 3 multipath channel models. The plots of receiver sensitivity versus SNR ($E_b/N_0$) are then depicted for all 3 channel models together which show that there are significant variations in the values of receiver sensitivity between the three models.

Using multiple power line receiving ports, the bit error rate performance results are then evaluated considering all three channel models as a function of Signal to Noise Ratio (SNR) for 8 number of OFDM subcarriers N and number of receivers L as a parameter. It is noticed that the BER performance improves with increase in the number of receiver ports. Also it is noticed that there is improvement in system performance with increase in the number of OFDM subcarriers N.

The required receiver sensitivity to attain BER=$10^{-6}$ are determined from the curves Fig. 3.5 through Fig. 3.22 and are plotted in Fig. 3.23, Fig. 3.24 and Fig. 3.25 for 4-path, 15-path and 5-path channel models respectively as a function of number of receivers (L) with number of OFDM subcarrier as parameter. It is noticed that there is significant improvement in receiver sensitivity with increase in number of receiver at a given value of OFDM subcarrier N for a particular BER=$10^{-6}$. There are further improvements with increase in the number of subcarriers.

Finally, the plots of improvement in receiver sensitivity are depicted in Fig. 3.26, Fig. 3.27 and Fig. 3.28 as a function of receiver number corresponding to 4-path, 15-path and 5-path models with number of subcarrier as a parameter. It is noticed that improvement is significant and of the order of 10 dB to 55 dB depending on the number of OFDM subcarriers.

The results obtained in this work are based on computer simulations using widely-accepted models to represent the power line channel with multipath phenomena. Analyses may be carried out in future with practical measurements in actual power line networks to verify the practicality of existing and new PLC techniques. Channel and noise measurements in Bangladesh power line grids should be conducted since the differences in topologies, structures and types of wire can affect the transmission behaviour.

We have used OFDM combined with diversity technique to improve the system BER performance. In future there are wide opportunities to combine space time coding (STC), MIMO, MC-CDMA etc. to further improve the system performance.

We have taken into account the multipath scenario of power line communication network. Though noise, attenuation etc. are also responsible for power system performance degradation, they can also be considered with different types of modulation and reception techniques to improve the performance of the BPLC system.

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