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SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

ULTRA WIDEBAND COMMUNICATION SYSTEM PERFORMANCE ANALYSIS FOR AA-LRT TUNNEL AT PIASSA

Thesis paper For The Partial Fulfillment of The Masters of Degree in Railway Electrical Engineering

by

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CERTIFICATE

This is to certify that the thesis entitled “Alternative Wireless Communication System Design for AA-LRT Railway Tunnels at Piassa” submitted by Mr. Mehari Belete, in partial fulfillment of the requirements for the award of Master of Degree in Electrical Engineering, with specialization of ‘Railway Electrical Engineering’ at Addis Ababa University; Addis Ababa Institute of Technology, is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter presented in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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ABSTRACT

Railway transport is effective and reliable only if it has best communication and signaling system with safety, reliability and good quality of service which are maintained by railway management and communication system. By implementing latest technologies for railway communication railway transportation can be made safer, efficient, and more accessible. This research work focuses on the study of Ultra wide band (UWB) radio based wireless communication system as an auxiliary or alternative communication system for Addis Ababa Light rail transit (AA-LRT) tunnel at piassa (Gyorgis), whose main task is to maintain an uninterrupted data transmission between train driver to wayside controller. The much larger bandwidth of ultra-wideband allows a very high data rate (up to maximum 480 Mbps), which is beneficial in case of emergency in railway networks. This research studied the rectangular shaped railway tunnel environment as wireless channel by considering ray theory model of wave propagation (modal analysis and ray tracing) and the effect of the curvature of the tunnel on the wave propagation. In this thesis work the frequency response, channel impulse response and path loss for different distances between transmitter and receiver and also the effect of fading over the channel is evaluated. The evaluations have been used to model the effects of tunnel propagation, including curves inside the tunnel. Then three standard wave shapes has been tested with the modelled channel to observe the phase shift and time delay provided by the considered channel model which behaves as a multipath fading channel with additive white Gaussian noise. Lastly to check the quality of reception bit error rate performance has been evaluated for BPSK and OOK modulation techniques.

Finally, a complete propagation model combining both modal analysis and ray tracing has been applied to predict the propagation loss inside the tunnel. So to maintain the continuity of communication it needs to install ultra-wideband trans-receiver over the specific interval.

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LIST OF ABBREVIATIONS

Abbreviations Description

AA-LRT → Addis Ababa Light Rail Transit
ATCS →Advanced Train Control Systems
ATP →Automatic Train Protection
ATO →Automatic Train Operation
ATS →Automatic Train Supervision
BER→ Bit Error Rate
BPSK →Binary Phase Shift Keying
CBTC →Communications-Based Train Control Systems
CCCS →Command Control and Communications Systems
EPLRS →Enhanced position and location reporting system
ERC →Ethiopian Railways Corporation
ETCS →European Train Control System
FCC →Federal Communications Commission
GO → Geometrical Optics
GSM-R →Global System for Mobile communications version for the rail industry
ITCS →Incremental Train Control Systems
LOS →Line of Sight
MGF →Modified Gegenbauer Functions
MPC → Multi path components
NLOS →Non Line of Sight
OOK →On-Off Keying
PSD →Power Spectral Density
PTC →Positive Train Control
PTS →Positive Train Separation
S–V →Saleh and Valenzuela model
TETRA →Terrestrially Trunked Radio
UWB →Ultra Wide-Band

Chapter 1

INTRODUCTION

1.1. Background

In many ways the technologies underlying train communications systems have advanced little in the time since the first modern rail systems were established 200 years ago. Many rail networks still use basic “Mark I eyeball” visual signaling systems that would not be unfamiliar to a locomotive operator from the 1800s [6]. However, new wireless data technologies now make it possible to create train communications systems that are as advanced as the electric, maglev, and hydrail locomotives that are powering the train systems of the future.

The railway applications of today, tomorrow, and beyond demand *more* bandwidth, *more* real-time response time, and *more* reliability from their communications networks whether they be intra-train, train-to-ground, or track side networks.

In wired communication data exchange takes over some physical cables like optical fiber cable, coaxial cables etc. which of-course is a fast mode of transmission but have some limitations like installation problem, cost of installation, maintenance cost & time and the safety concern. While the advancement in wireless communication system enables it to apply in almost all sectors for the exchange of information and data in different formats.

Railway transportation is one of the areas of interest where the benefits of wireless communication technology can be applied for the betterment of railway industries. Wireless communication assists the vehicular monitoring system by reducing the maintenance and inspection needs of railway transportation along with safety and reliability.

Wireless communication system has become integral part of modern transportation system. Advancement in communication technology makes the human effort very less to analyze and avoid the problems associated in data transmission.

To meet modern needs, train communications systems must improve in three key areas: bandwidth, response time, and reliability.

- ✓ **Bandwidth:** The contemporary traveler expects a higher level of convenience, safety, and service. To fulfill these high expectations train operators now use telephony and data systems for real-time surveillance and modern passenger infotainment systems to deliver rich entertainment and information content to passengers, including news, weather, games, and even Internet access. Naturally, all of these applications need enough bandwidth. In addition, with enough bandwidth it becomes possible to consolidate voice, video, and other operational data on one train control network, dramatically simplifying operations and maintenance.

Telephony, data, and passenger infotainment systems are all bandwidth-hungry applications that tax the limits of existing networks.

- ✓ **Response Time:** The old-fashioned method of train control relied on human operators who were given directions through some combination of radio, visual signals, and track circuits. This method had a slow response time, and for safety reasons tracks were divided into long “segments” or “blocks,” with only one train allowed on a block at a time to prevent catastrophes. The introduction of Communication-based Train Control (CBTC) technology improved the efficiency of train operations by allowing operators to reduce the length of the blocks without compromising safety. However, the efficacy of a CBTC system is highly contingent on the communications response time. A system with a long response time is cumbersome to use and provides little improvement over legacy communications systems, while with real-time response time the CBTC can safely and efficiently maximize the number of trains on the track at once.

As CBTC takes over from human operators, fast response time becomes central to smooth operations.

- ✓ **Reliability in a Harsh Environment:** As operators take advantage of the new capabilities of advanced train communications systems, more and more train systems depend on reliable communications. Next-generation communications systems need to be reliable enough to shoulder these new responsibilities. In particular communications must be sufficiently resilient to overcome the unique hazards of rolling stock operations: weather, shock, vibration, and electromagnetic interference. The EN50155 and EN50121-

1/2 standards are useful benchmarks for confirming that the communications devices are sufficiently robust for onboard and trackside applications, respectively.

The more train operators rely on their communications networks, the more reliable those networks need to become.

A secured, robust, reliable and converged telecommunications network is therefore essential to support different information exchanges, whether man-to-man, man-to-machine or machine-to-machine. This helps transport operators to fulfill their mission while keeping the highest level of global security and increasing passenger satisfaction (through outstanding punctuality and more services).Rail operators are not only going to compete against each other but also with other means of transportation, such as planes or cars, and in this context offering more comfort and entertainment to passengers is not an option. Amongst the different applications (or « services ») to be carried by the telecom network, one can distinguish two main families with very different constraints and specifications:

- ✓ Vital applications and
- ✓ non-vital applications

Vital Applications:-related to signalling and control/command of equipment. Such applications require generally a low bandwidth (some 10 to 100 kbps) but a very high degree of availability (at least99.99%), robustness and liability (typically a packet error rate of 10^{-3} for an approximately 200 byte packet length). Such performance indicators have equally to be fulfilled under high speed mobility.

Non-vital applications:-related to Passenger Information, remote maintenance, on-board video surveillance, CCTV for track or platform monitoring, internet access, etc. Such non-vital applications generally require much higher bandwidth (several 10s of Mbits/s in both direction train-to-ground and ground-to-train), together with lesser robustness constraints (a packet error rate of 10^{-2} for an approximately 1Mbyte packet length).

1.1.1. Existing train-to-ground communication solutions

A moving train cannot obviously be connected to ground based infrastructure by any other means than radio communication. Such radio systems have long been based on analogue technology, dedicated to voice and not adapted to carry data. Then digital technology became available in the market, with various bandwidth capabilities and distance ranges, supplied to different standards or even totally proprietary protocols.

Rail operators have implemented such technologies alongside their track and inside their vehicles, but without necessarily being interoperable, or with specific adaptation to match vital application requirements. It is quite common to see operators deploying several radios with different purposes in the same rail network and geographical area: ETSI TETRA / 3RP, IEEE 802.11a/n Wi-Fi, ERTMS GSM-R.

Propagation of wireless signals (radio wave) may take open air or the guided transmission system as the case in this thesis (tunnel). The transmitter or the receiver may be inside or outside the channel and either moving or fixed. In this case of railway tunnel the transmitter is fixed at some points in the tunnel and the receiver is moveable as it is mounted on the moving train. Tunnel environment is assumed as multipath fading channel with added white Gaussian noise. Based on this channel model detail analysis has been done to study the effect of path loss and fading over the channel characteristics. The existing narrowband wireless communication system do not have the capability to sustain the heavy attenuation provided by tunnel environment, as it has limited bandwidth so optimal receiver designing become bit difficult. This problem can be avoided by replacing narrow band communication with a wideband communication technology.

There are many wide band signals with their own advantages and disadvantages. Ultra wideband is the latest and rapidly growing technology with extremely large band width low transmission power. Low power spectral density of UWB signals makes it to coexist with other narrowband and wideband signal without any interruptions. Ultra wideband technology has the capability to provide simultaneous ground to train communications, train location and to prevent from possible hazards due to collisions. UWB provides a challenging, economically sensible, as well as technically effective alternative solution to existing signalling technologies used in railway communication systems.

1.2. Problem Statement

Existing trackside networks often rely on cables between wayside cabinets to deliver communications. This fragile cable can become a weak link in the trackside infrastructure, as it can be targeted by vandalism or damaged by the weather. In addition, the valuable metal is a frequent target of thieves, and the many meters of cable needed to support a true track side network represent a significant ongoing replacement and maintenance cost. Replacing the cables with wireless network units in each wayside cabinet eliminates this vulnerability.

In case of ERC, AA-LRT the radio wireless communication system there should be a redundancy configuration adopted for critical parts to enable automatic switch-over in case of failure and to ensure 24 hour uninterrupted operation of the system. Four sets of directional antennas are used in an underground section tunnel of Length 655 m. The system is operated under the frequency bands of 400MHz or 450MHz [30].

Inside tunnels wave propagation faces the problem of multipath fading, frequency and distance dependent attenuation. Existing narrowband communication system cannot withstand these attenuations. This motivates to use a latest wireless technology called as Ultra wideband communication to overcome the problem of heavy multipath attenuation. UWB has a large bandwidth of the order of 500 MHz and very high data rate beyond 480 Mbps. This makes it a prominent technology to avoid the problem of multipath fading and other distance dependent losses. Further the high data rate allows video data streaming which is help full to develop driver less subway systems.

1.3. Significance of the thesis

Preventive maintenance is a more and more common tool used by railways operator to significantly enhance their operational efficiency. By permanently and remotely monitoring the status of key elements of the rolling stock, maintenance actions can be planned in advance upon detection of warning information before the fault becomes an actual problem. Today, the remote monitoring is usually performed using commercial low speed 2G technologies [6]. Such services are driving the huge increase in bandwidth requirement, and consequently a new generation of train-to-ground transmission will soon have to address these needs, while following telecom industry standards with minimum (or no) rail specific adaption in order to avoid costly solution and rapid obsolescence [6].

The new wireless applications primarily focus on its high data rates (> 100Mb/s) and high bandwidth for indoor short distance operation (<20 m) applications [44]. All wireless systems must be able to deal with the challenges of operating over a multi-path propagation channel, where objects in the environment can cause multiple reflections to arrive at the receiver. BER degradation is caused by inter-symbol interference (ISI) due to a multi-path propagation made up of radio wave reflections by walls, floor, ceiling and fixtures. Generally, 100 Mbps transmission was actually confirmed to be available for an allowable BER of 10^{-6} [38]. All stated problems need UWB as a suitable solution. So the problems stated so far will be eradicated by the use of UWB radio communication system having the following advantage:

These are some of the advantages of an UWB signalling system in comparison to narrow band signalling systems:

- High data rate;
- Very precise range measurement for tracking systems;
- Excellent performance in difficult environments such as those with multiple reflective paths and interferers;
- Easily adapted to dynamic data rate systems;
- Ability to track simultaneously a large number of tags because of very short pulse-width.

So this study is found to be significant and coming up with better, safe, secure, reliable, robust and advanced system should not be overlooked.

1.4. Objectives of the thesis

1.4.1. General Objective

The main and general objective of this thesis work is to design Ultra- wideband (UWB) radio based wireless communication system for AA-LRT railway tunnel at piassa.

1.4.2. Specific objectives

To design a wireless channel model for railway tunnel and to study the effect of multipath fading and distance dependent path loss over the channel frequency response and channel impulse response.

- To study the effect and additional loss on UWB radio propagation due to the curve in the tunnel.

- Three standard UWB pulse shapes (Gaussian pulse, Gaussian mono-pulse and truncated sinusoidal pulse) propagated through modelled channel, to calculate the phase delay and time delay provided by the channel.
- To evaluate the bit error rate performance by considering BPSK and OOK modulation technique over the channel with increasing distance between transmitter and receiver.

1.5. Literature review

To give the answer to the developing demand for high-performance wireless communication systems inside tunnels, many investigators have performed simulations and measurements of wave propagation in the last four decades. Based on different methods, such as vector parabolic equation (VPE), geometrical optics (GO), modal analysis, finite-difference time-domain (FDTD), etc., more and more researchers are inclined to analyze the propagation characteristics by separating various zones along the tunnel. This segmentation-based thought is gradually formed but still lacking in unanimous consensus on the zone division and corresponding propagation mechanism modeling in each zone. In general, to describe the propagation inside tunnels, a large number of models are presented in a two-slop e curve that the losses are described by two different expressions. In these models, the dividing point (also known as the break point) between two slopes separates the whole process into two segments. Before the break point is the near region, where the high order modes are dominant; waveguide effect has not been established, and therefore, the signal undergoes larger loss and stronger fluctuations. After the break point is the far region, where the high-order modes have been greatly attenuated; the fundamental modes guide the propagation so that the wave suffers smaller loss and slight fading.

In the past two decades, wireless telecommunications have experienced an explosive growth. On the one hand, a wide variety of advanced wireless telecommunication technologies have greatly facilitated our daily lives and thus stimulated an increasing demand for railway transportation communication. However, the increasing demand for railway transport has led to an exponential growth of signalling and communication traffic which has set a formidable challenge to the wireless system capacity [6].

Signalling and communication system used to control the speed of train, to avoid possible hazards and punctual operation of the trains. Trains run over the track on the basis of some rules and guidance, which are must for safety. The most important rule is that two trains should never occupy the same position over the track simultaneously. To ensure that it will not happening, operators and controllers uses signaling and communication [22] and [12]. With the developing technologies railway signaling and communication systems also developed over the past year as the manual signalling and wired communication replaced by the automatic signalling and wireless communication systems. Latest techniques of data exchange enable to apply the wireless communication for train monitoring which improves the safety and reliability by reducing maintenance and inspection requirements [9].

Many literatures has been reviewed that

1.5.1. Wireless Propagation Channels and channel modelling

A wireless propagation channel is the medium linking the transmitter and the receiver. Its properties determine the information-theoretic capacity, i.e., the ultimate performance limit of wireless communications, and also determine how specific wireless systems behave. It is thus essential that to know and understand the wireless propagation channel and apply this knowledge to system design.

Wireless channels differ from wired channels by multipath propagation, i.e., the existence of a multitude of propagation paths from transmitter and receiver, where the signal can be reflected, diffracted, or scattered along its way. One way to understand the channel is to consider all those different propagation phenomena, and how they impact each Multi Path Component (MPC).

The interference of the different MPCs creates not only fading (i.e., variations of the received power with time and/or place), but also delay dispersion. Delay dispersion means that if a signal of duration T is transmitted, the received signal has a longer duration T’. Naturally, this leads to Inter-Symbol Interference (ISI) [42].

In wireless telecommunications, the term “path loss”, in decibel (dB), is defined as the transmitted power minus the received power. Thus, path loss represents the signal attenuation introduced by the propagation channels [42]. It is always a positive quantity. Although the basic propagation principle in indoor environments is similar to that of outdoor environments, the indoor radio propagation has its specificity as follows:

- More reflections, diffractions and refractions are possible to occur in indoor radio propagation due to the rich presence of obstacles, such as walls and furniture etc. The sizes of indoor scenarios are normally smaller than those of outdoor scenarios.
- Unlike outdoor environments which are full of high speed moving objects and mobile users, indoor environments are usually full of low speed moving people. Hence, the Doppler shift in indoor environments is negligible [35].

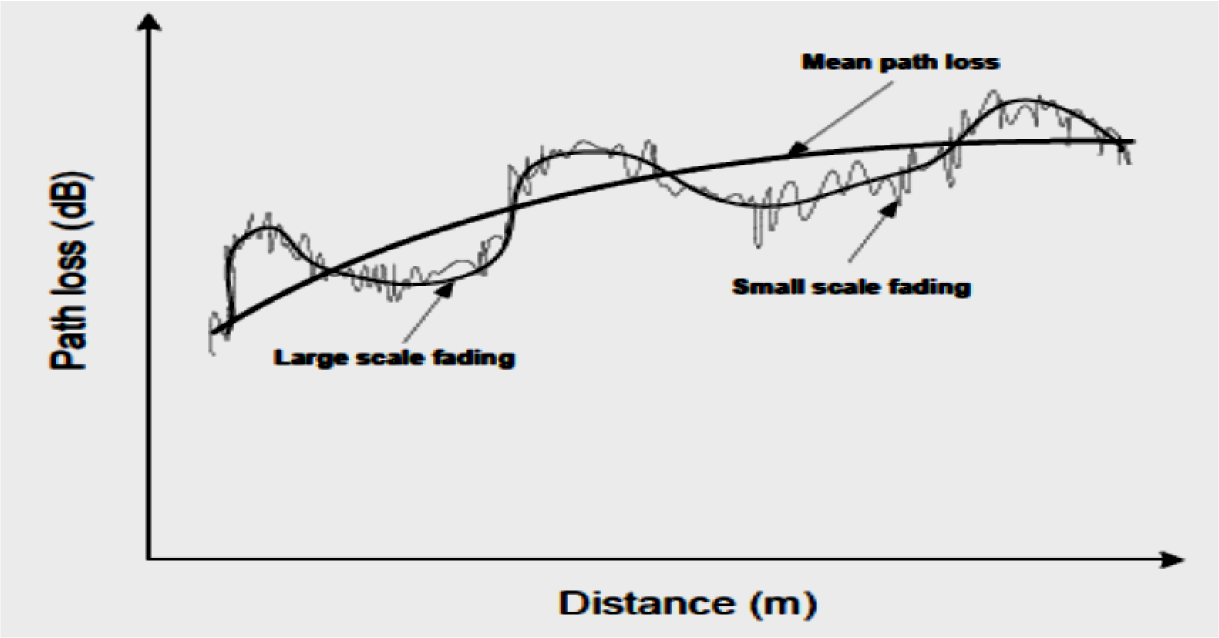


Figure 1.2 path loss along the distance

The commonly used radio propagation modeling methods for indoor environments can be mainly categorized into the following four types [43]:

1.5.1.1. Empirical models

Empirical models are usually extracted from channel measurements conducted at some typical places. They are extracted by fitting the measurement data with some simplified mathematical formulas or distribution functions. Thus, empirical models are normally very easy to implement and with very low computational load. However, since empirical models are extracted from measurements conducted only at some typical places, they retain some general channel characteristics without taking into account the specific propagation environments. For a specific propagation scenario, empirical models usually suffer from a low level of accuracy. The widely used empirical models for indoor environments include, for instance, the one-slope model, wall and floor factor models, COST231 multi-wall model and linear attenuation model etc.

1.5.1.2. Stochastic models

Stochastic models are usually used to model the random aspects of radio channels with random variables, e.g. fading characteristics of radio channels. Stochastic models require very little information of the propagation environments. For radio propagation channels, there exist two typical types of fading: the large scale fading and the small scale fading. The large scale fading characterizes the signal strength variation over large distances [43]. On the contrary, the small scale fading characterizes the rapid fluctuations of the received signal strength over very short travel distances (usually a few wavelengths). The large scale fading and the small scale fading are usually modeled with stochastic models. For instance, the large scale fading, i.e. the shadow fading, is usually modeled to be the Log-normal fading, and the small scale fading is widely modeled to be the Rayleigh, Rice or Nakagami-m fading etc. [35].

1.5.1.3. Deterministic models

Deterministic models simulate the real physical propagation phenomenon of radio waves. Deterministic models are based on the Maxwell’s equations describing the behavior of electromagnetic field and take into account the specific propagation environments. Thus they usually possess a high level of accuracy. Since deterministic models take into account the specific propagation environments, they are also called site-specific models. The predicted results provided by the deterministic models are deterministic, i.e. the predicted results are always the same no matter how many times you rerun it if there is nothing changed in the simulated scenarios. Although deterministic models have the advantage of high accuracy, they have also the disadvantage of heavy computational load. Moreover, the high accuracy of deterministic models depends strongly on the accuracy of databases of the simulated scenarios.

Ray-optical models and Finite-Difference Time-Domain (FDTD) models are the two widely used deterministic propagation models.

1.5.1.4. Semi-deterministic models

Semi-deterministic models are the combinations of deterministic models and stochastic models or empirical models. Thus, semi-deterministic models benefit from both deterministic models and stochastic models or empirical models. For instance, semi-deterministic models usually require less computational time and lower computational load than deterministic models, but possess a higher level of accuracy than stochastic models or empirical models. The existing semi-deterministic models include for example, the Dominant path model, the Motif model and the Geometry-based Stochastic Channel Models (GSCMs) etc.

A communication channel can be air (vacuum) or a physical device and also there are situation in which the communication channel can be a wave guide as in the case of railway tunnel, in which the tunnel is considered as oversized waveguide. Wireless communication in railway tunnel suffers many losses. The above discussed radio propagation modelling methods can be applied to select better model and model the channel to its best channel characteristics.

1.5.2. Radio propagation models for tunnels

The knowledge of radio propagation environment is essential for specification and installation of wireless communication systems. The statistical properties of wireless channel, for example probability density function of received signal strength, fade durations, level-crossing rate, etc., taken into consideration by statistical channel models, are relevant for specifying transmitter and receiver characteristics and link budget calculation. For the installation of wireless communication systems the radio wave propagation models are applied, characterized by the radio environment as a function of frequency and distance between transmitter and receiver.

These radio propagation models typically predict path loss, power delay profile or delay spread for specific transmitter and receiver location. Parameters and mathematical expressions are obtained from measurements of received signal strength and delay spread so that the expressions follow the level of measured signal. The accuracy of empirical models depends on the degree of similarity between the environment in which model parameters are estimated and the environment to which the model is applied.

When a plane radio wave hits a facet, it partially reflects and partially penetrates the wall. The energy of radio wave reflected from the facet is calculated using reflection coefficient r_i, while the energy transmitted through the wall is estimated using transmission coefficient T_i. Assuming a typical radio propagation environment in tunnels, where one medium is air and the other is thick concrete wall, the reflection coefficient depends on the signal wavelength λ, angle of incidence θ_i, relative permittivity ε_r, conductivity σ and relative permeability μ_r of the wall [42] and polarization of the radio wave. The described reflection mechanism and the assumption that the angle of incidence is equal to the reflection angle (Snell's law), provide the basis for the Geometrical Optics (GO) approach to path loss prediction. However, radio waves spreading behind obstacles cannot be described precisely just by reflection, therefore radio wave diffraction is introduced into the propagation model. Radio wave diffraction obeys Huygens's principle, which says that each point on a primary wave front can be considered as a new source of a secondary spherical wave.

Attenuation in a rectangular tunnel depends on the signal carrier frequency f_c, the width and height (a, b) of the tunnel, the permittivity of its walls ε, and their roughness and, in particular, on the propagation mode. In tunnels, radio signal propagation can be divided into near field and far field propagation regions. In the former, the propagation is affected by several modes. Attenuation in the far region depends only on the few lower order modes, typically only on one. The frequency of the propagation signal does not affect the power distribution among modes, but strongly influences the propagation constant [42].The field magnitude in rectangular and circular tunnels as a function of axial distance can be divided into a near field region and a far field region. In the near field region, the electromagnetic field consists of many modes which interact and produce wide and rapid variations. In the far field region, low order modes determine the electromagnetic field. In addition, the measurements prove the trend of decreasing overall attenuation as a function of increasing frequency [42]. The multimode waveguide model gives an analytical expression for a path loss and delay spread calculation at any position in the tunnel. It confirms that the mode of attenuation depends mainly on tunnel dimension and operating frequency, while the power distribution among individual vicinity of the transmitter, signal attenuation is high and varies.

Since the higher modes of attenuation decrease rapidly, their contribution to the received signal power level is negligible. Signal attenuation and its variation are reduced as the distance from the transmitter increases.

Humidity, pressure, air temperature inside the tunnel, and the construction materials have negligible impact on signal propagation inside tunnels [42]. Two radio signal propagation regions are identified. The boundary between them is calculated using the ray tracing model, while mode analysis is applied to compute the propagation attenuation in both regions. The propagation field description is based on the superposition of appropriate characteristic modes whose amplitudes are effectively evaluated by preliminary ray tracing procedure. In order to extend prediction capabilities to real tunnel environments including possible route curvatures, the possibility of associating each mode with proper optical bouncing on the tunnel walls is included.

1.5.2.1. Ray Tracing Based Channel Models

Ray tracing approach, widely used in radars and recently in computer graphics, has also been applied to predict path loss in tunnels. Ray tracing models are based on a geometrical optics approach, where radio wave is approximated by ray. The facets where radio rays are reflected and diffracted are assumed to be much larger than the wavelength of the radio ray. The basic principle of ray modeling is given by the following equation[39].

$$L_R[dB] = -10\ log_{10}\left[\left(\frac{\lambda}{4\pi}\right)^2 \left\|\frac{G_t}{d} + \sum_{i=1}^{\infty}\frac{G_i R_i \left(j\ \frac{2\pi}{\lambda}(d_i - d)\right)}{d_i}\right\|^2\right]$$

Where G_t and G_i are the gains of the transmitting and receiving antennas, which correspond to the path of direct and i^{th} reflected ray respectively, and d and d_i are the path lengths of the direct and i^{th} reflected rays. R_i is the product of the reflection coefficients of all walls from which the i^{th} ray is reflected [40]. The received signal is the sum of the direct ray and all reflected rays. The difference in the phases of the received rays results in the rays being added constructively or destructively. The constructive and destructive signal summation is presented as a variation of signal power with distance.

Two basic approaches for calculating ray paths are: (i) the Shooting and Bouncing Ray (SBR) method and (ii) the image method. In the former, rays or ray tubes are shot from the transmitter in all directions. The rays are then reflected from obstacles before they reach the receiver. The receiver is represented by a reception sphere whose radius depends on the path length of a particular ray and on the angle between neighboring shot rays. The computational complexity of the SBR method depends on the number of objects in the environment and the number of shot rays. The tunnels can be represented by a small number of facets, which makes this method efficient in tunnel propagation environments.

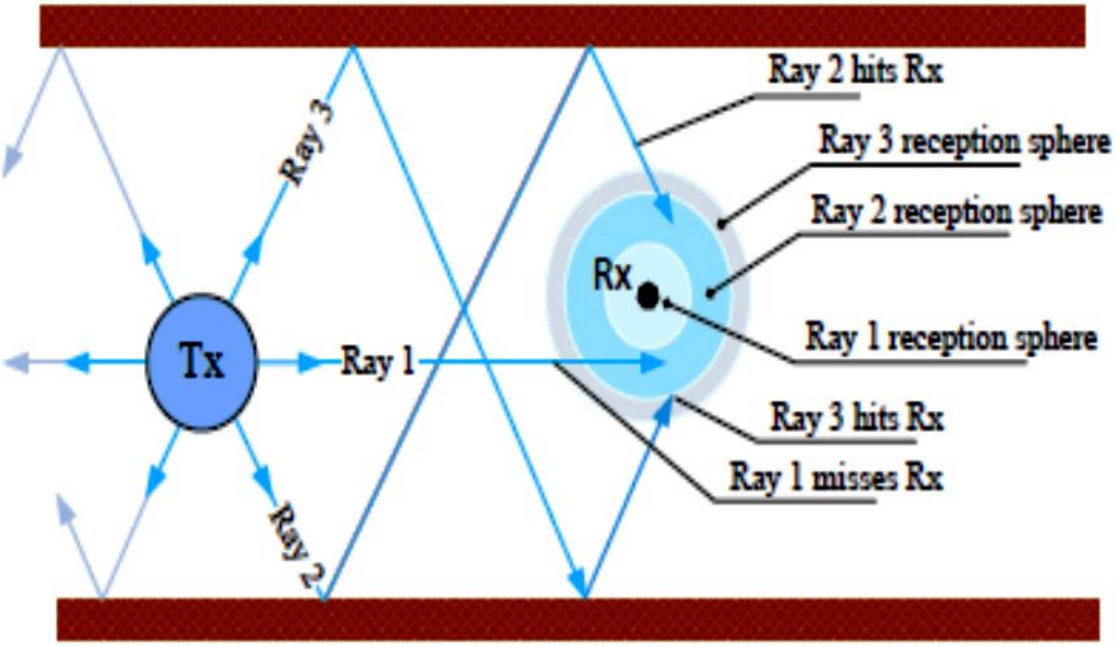


Figure 1.3 Shooting and bouncing (SBR) method in tunnel 2D

The ray tracing model can be simplified for rectangular tunnels, by converting the three dimensional radio signal propagation model into a simpler, two-dimensional model [39**]**. The approach significantly reduces the complexity and improves the efficiency. The approach takes into account all the rays that reach the destination after a random number of reflections, and incorporates the influence of incidence angle, material dielectric constant, antenna diagram and polarization, wall roughness and the tunnel cross section shape and size.

The propagation model which involves the ray launching, ray bouncing and adaptive cube for ray reception is developed to obtain path details inside the tunnel. A modified Shooting and Bouncing Ray (SBR) method [39] provides a relatively accurate calculation of the radio signal propagation, especially for tunnels where reflection is the dominant phenomenon. Modified ray launching technique is used to model the radio wave propagation in arched-shaped straight tunnels and rectangular curved tunnels using a reception sphere.

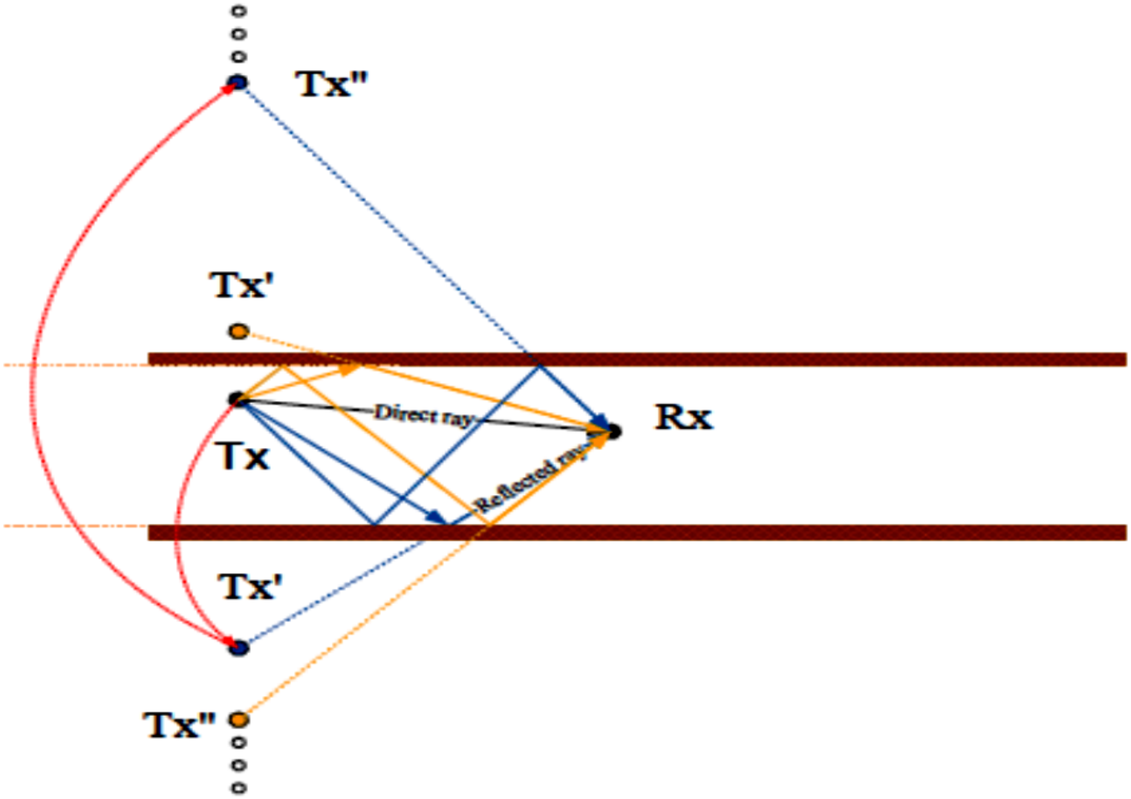


Figure 1.4 Image ray tracing method in tunnel-2D

Also minimization of the paths length is done according to the Fermat principle. In addition, an adaptive identification of multiple-ray technique has been developed based on the localization of reflection points [40].

1.5.3. Parameters affecting radio propagation in tunnels

Radio wave propagation in tunnels depends on radio signal frequency, tunnel cross sectional dimensions and shape, curves in the tunnel, surface roughness, electromagnetic properties of walls, obstacles and their positions, polarization and radiation patterns of the transmitter and receiver antennas [40]. The impact of these parameters on radio wave propagation is discussed in the following subsections.

1.5.3.1. Tunnel Geometry

Tunnel cross section has an important impact on attenuation rate. For various forms of tunnel cross section, a general equation for radio signal attenuation in dB/m is **[83]**:

$$\alpha = k\lambda^2 \left[\frac{\epsilon_r}{\mathrm{a}^3\sqrt{\epsilon_r - 1}} + \frac{1}{\mathrm{b}^3\sqrt{\epsilon_r - 1}} \right]$$

Where a is the maximum tunnel width, b the maximum height, and $\boldsymbol{\varepsilon_r}$ is the relative permittivity of the tunnel walls and floors. The value of coefficient **k** varies with the shape of the tunnel: values k = 5.09, **4.343**, 5.13 and 4.45 are used for circular, **rectangular**, arched and oval tunnels, respectively. It was demonstrated that the radio signal attenuation in rectangular and elliptical tunnels can be calculated using the attenuation coefficient for a circular tunnel, with the equivalent cross section area while for an arched tunnel, the attenuation coefficient for a circular tunnel can be used only at frequencies higher than 1.2 GHz [40].

The shape and the dimension of the tunnel cross section and curves in the tunnel have significant impact on radio signal propagation [40]. The influence of cross section on the attenuation is distinctive, particularly when signal frequency increases, where also the impact of curves, slopes and additional branches in tunnel is more emphasized. Tunnel curves may prevent direct visibility between the transmitter and receiver, thus affecting radio signal propagation, since reception of the direct wave is blocked. The radio signal delay spread is increased and the received power reduced by the decrease of the curve radius. In straight tunnels, the radio signal attenuation decreases with increased frequency while in curved tunnels it increases. Under NLOS conditions only reflections and diffractions contribute to the received signal strength. For reliable communication it is preferable to install additional antennas and thus maintain the conditions of direct visibility (LOS) between adjacent antennas.

1.5.3.2. Electromagnetic Properties of Tunnel Walls

In most tunnels, the influence of conductivity can be neglected, since it is not sufficiently high [40]. As long as the dielectric constants of side walls, roof and floor are approximately equal, the attenuation rate of the vertically polarized mode is greater than that of the horizontally polarized mode as long as the tunnel width is larger than its height. In such tunnel, the horizontal polarized antenna is more appropriate than vertical polarized one [39]. The dominant mode attenuation, which is the result of the penetration into lossy tunnel dielectric walls, can be reduced by metallic strips placed on the wall surface. The solution is particularly suitable for the frequencies at which the signal wavelength is comparable with the tunnel cross section dimension.

1.5.3.3. Antenna Radiation Pattern and Position

The signal attenuation can be reduced by using antennas with suitable radiation pattern at appropriate locations. While the Omni-directional antennas offer better signal coverage in NLOS tunnel regions, directional antennas perform better in LOS regions [35]**.**By moving the transmitter towards the wall of the tunnel; propagation becomes more complex, while the signal attenuation and delay spread increase. In an empty straight rectangular tunnel the delay spread is greater for horizontally polarized antennas than it is for vertically polarized antennas if the tunnel width is greater than the tunnel height [35]. In such tunnels the horizontal polarized wave attenuates less than the vertical one, because the attenuation of waveguide mode becomes lower with larger horizontal cross section dimension. In this case contributes to the electromagnetic wave level in far field. Consequently, the electromagnetic wave attenuation is also lower for the horizontal polarization than it is for the vertical one [38]**.** In addition, the reflection coefficients on the horizontal ceiling and floor are larger than those on vertical walls, which additionally contribute to higher attenuation of vertical polarized electromagnetic waves [43].

1.5.3.4. Obstacles

Since reflections from train increase the delay spread, sufficient bandwidth is required in order to ensure communication quality. Due to the metal surface, the train has relatively small effect on the received signal level. When the train is passing the transmitter the near shadowing effect is created, which causes the attenuation that lasts up to several seconds. The attenuation value depends on the ratio between the train and the tunnel cross sectional dimensions and can reach up to 32 dB for passenger train in narrow one track tunnels [40]. Radio signal measurements in tunnels show that the radio signal propagation path losses caused by vehicles in tunnels depend mainly on their *number* and *dimension*, rather than on their relative position within the tunnel.

1.5.4. UWB radio channel models

Model	Description of arrivals	Comments
Modified delta-k model (extended by Hashemi to indoor channels)	Modified Poisson arrival process with a 2-state Markov process modelling arrival rates to allow clustering/ spreading of arrivals	Based on large data set at distance separations of 5-30 meters. 5nsec resolvability.
Saleh-Valenzuela model	Cluster model with cluster arrivals and rays within a cluster are modelled as Poisson process with different arrival rate and MIP decay factor	Recently extended to model UWB channel by Cramer/Scholtz
Ray tracing model	Deterministic model using 3-D model of indoor channel taking into account reflection and diffraction of electromagnetic waves from objects based up on material.	Too many reflectors to track. Difficult to extend to different channels.
Cassioli, Win, Molisch model (VCT 2001)	Based on office channel measurements with UWB wave forms and 2nsec resolvability	Larger number of realizations needed for statistical accuracy

Table 1.1 UWB radio channel models

1.5.5. ERC AA-LRT, N-S Line profile

The N-S (Phase I) Project starts from the east of St. George Church in the north and turns towards the south after a section laid along the north of Merkato Market, then passes through the west of the market to Chad St. and integrates with the E-W line. Then the line is laid towards the east and turns towards the south after arriving at the west of Mesekel Plaza, and finally arrives at Kalliti, which is the terminal end in the south, after crossing beneath Meshualekia Bridge and Sino-Ethiopian Friendship Bridge. The line passes through main roads such as Fitawrari Gebeyehu St., Gyorgis St., Central African Republic St., Dej. Mekonin Demissew St., Dej. Bekele Weya St., Chad St., Ras Mekonin St., Ras Biru St., Sierra Leone St., Beyene Aba Sebsib St. and Debre Zeit Rd. It has the sub-grade section about 10.057km in length, the elevated section about 5.977km in length (including a common rail section 2.662km in length), and the underground section about 0.655km in length. A total of 22 stations are designed on the line, among which there are 8 elevated stations (including 5 common rail stations) and 1 underground station. The rest are built on the ground. The maximum and minimum intervals between stations are 1.972km and 0.435km respectively. The average station intervals are 0.773km [30].

1.5.5.1. Main Design Principles

- To meet the demand of operation and management, the communication system of the Project should be built into a safe, reliable, economical and practical communication network with reasonable functions, flexible networking and, expandability; it also should be able to transmit various information such as voice, data, images, video, etc.
- Its communication system should not only meet the requirements of the Project, but also reserve necessary conditions for follow-up projects and lines to be introduced.
- The communication system of the Project is composed of the following subsystems: transmission, telephone, radio communications, video monitoring, communications power supply and earthing.
- All communication subsystems should have the function of centralized monitoring and management, and can carry out real-time monitoring, fault location, system configuration and records keeping.

- Redundancy configuration should be adopted for critical parts to enable automatic switch-over in case of failure and to ensure 24 hour uninterrupted operation of the system.
- The equipment and cable adopted by the system should comply with the national technical standard of China and the ITU recommendations, etc.
- The communication system should adapt to ground conditions, conditions of viaduct and tunnel and the properties of electric railway should be fully considered to avoid locating within the equipment clearance.

1.5.5.2. Type of Services and Bandwidth Requirements

S/N	Name of Service	Species	Interface Type	Bandwidth Allocation	Remarks
I - Internal Subsystems of Communications Systems					
1	Tel.	Voice	FE	100Mb/s	Bus shared
2	Radio Communication	Voice	FE	10Mb/s	Bus shared
3	Video monitoring information	Data	FE	2*100Mb/s	Bus shared
4	Communications power network management	Data	FE	10Mb/s	Bus shared
II - Other Systems					
5	Monitoring information of the substation	Data	FE	10Mb/s	Bus shared
III - Reservation					
6	Reserved	Data	FE	4×10Mb/s	Bus shared

Table 1.2 types of service and required bandwidth in railway communication [30]

As this is intended by Ethiopian railway corporation (ERC), there should be a communication system with high data rate. Selection of transmission equipment should conform to the principles of advanced technology, safe, reliable and economic. Equipment should be equipped with flexible and minimum kinds of hardware which are easier to upgrade, expand and re-configure.

1.5.5.3. Radio Communication System

Radio communication system is an important supporting measure to ensure traffic safety, to increase transportation efficiency and management level and to improve service quality. This system provides radio communication services for all the related users in the control center and the depot, including dispatcher, driver and staff, operating personnel, site personnel, etc.

Coverage range of wireless field density of radio communications system in the Project includes the whole line of light rail operation tracks such as tunnels, on-ground and overhead lines and depots, the following method of field strength coverage is recommended:

Outdoor directional and Omni-directional antennas are adopted in field strength coverage of the on-ground and overhead operation tracks and the depots. Directional antenna is adopted in field strength coverage of underground tunnels and underground stations.

- ✓ **Vehicle radio set**

Vehicle radio set (including host machine of station, antenna, control box, power supply unit, installation frame, etc.) is set up in the driver's cab at both ends of the train, and the low-profile disk antenna is installed on top of the train.

Directional antenna can be divided into two types, one of which is installed in the iron tower (derrick) on top of the inter-section substation to be used in on-ground and overhead lines; the other type is installed in the underground tunnels to cover the underground lines.

- ✓ **Frequency band selection**

The system is operated under the frequency bands of 400MHz or 450MHz, and the specific frequency band is to be determined after negotiation with wireless management department of Ethiopian in the next stage. In order to meet the wireless coverage requirements, this design is calculated based on two frequency bands such as 400MHz and 450MHz during the coverage plan.

- ✓ **Underground antenna feed design**

According to the calculation of field strength coverage and taking the actual conditions of the site and the city scale into consideration, the one-way coverage distance of ground base station is considered to be 2.5 km. Length of the underground district is relatively short, so outdoor base station RRU is set up in the middle of underground district. Coverage could be realized by directional antenna in the tunnel.

Base station location	Mileage	Antenna configuration	Remarks
NS27 station	DK2+060	Four sets of directional antenna in tunnels	Length of under-ground section 700 m

Table 1.3 system configuration of AA-LRT tunnel at piassa

- ✓ **Interface with signal system**

Radio communications system is responsible for train-ground wireless transit channels to convey data information related to signal system, and the interface is located at the exterior line side of equipment room in the control center and the onboard radio set. There are four pairs of directional antennas in tunnels.

1.6. Thesis Organization

This thesis is organized in such a manner that the basic concept and achievements flow in smooth and favorable way. The first chapter of this thesis deals with the foundation of the work by running through different introductory concepts (significance & objective), chapter two deals with basics of wireless and its relation with railway communication. The third chapter of this thesis elaborates the wireless communication system in railway and goes through some challenges of wireless communication systems in railway tunnel. The fourth chapter is an introductory or overview of the fundamentals of Ultra Wide Band radio based communication system and its application for railway tunnel is dealt in the fifth chapter. Results and output of the thesis are discussed in detail in the sixth chapter. Then finally based on the results found a conclusion is drawn in the conclusion and future recommendation section which is chapter seven.

Chapter 2

WIRELESS COMMUNICATION SYSTEMS FOR RAILWAY TRANSPORTATION

2.1. Introduction

Wireless technology is rapidly evolving and emerging, and thus is playing an increasing role in the lives of people all over the world. Additionally, ever larger numbers of people are relying on the technology directly or indirectly.

Previously, wired network has proven its potential but nowadays wireless communication has emerged as a robust and most intellect communication technique. Each of these types of networking has their advantages and disadvantages according to its network characteristics. Wired and wireless networking has different hardware requirements, ranges, mobility, reliability and benefits.

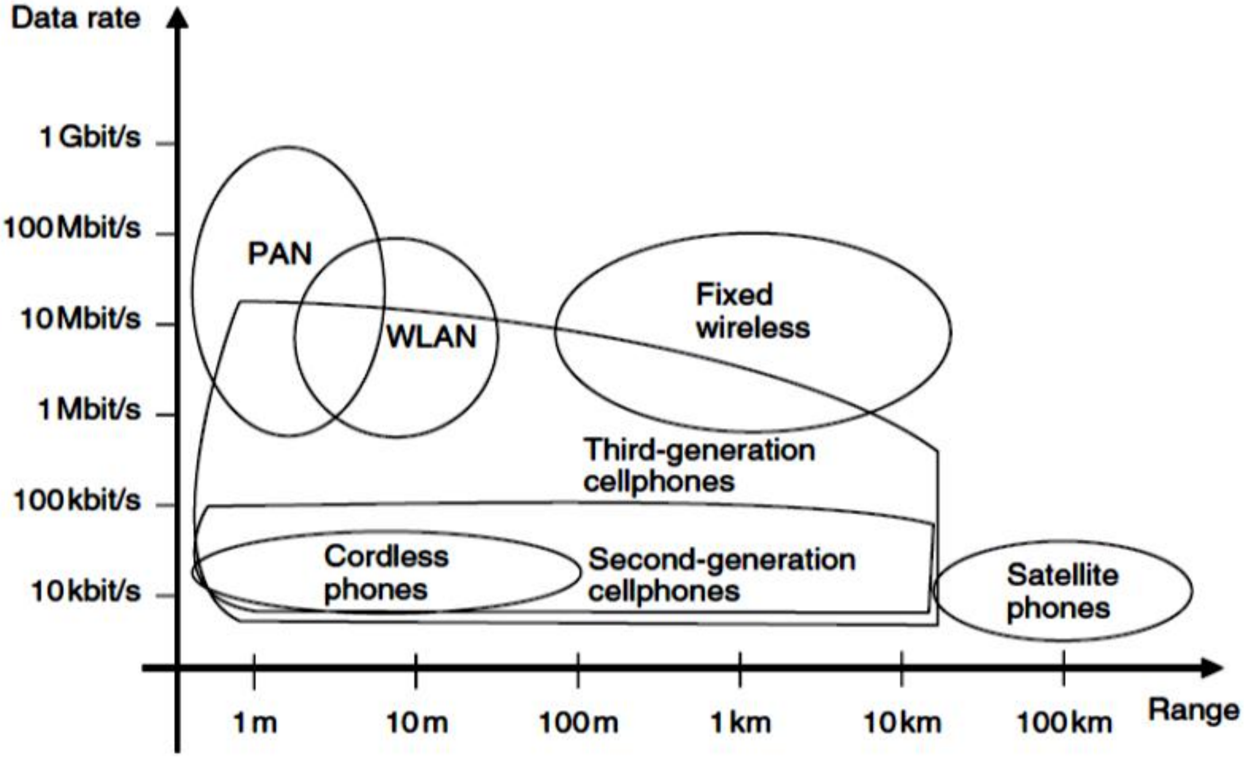


Figure 2.1 Data rate versus range for various applications [11]

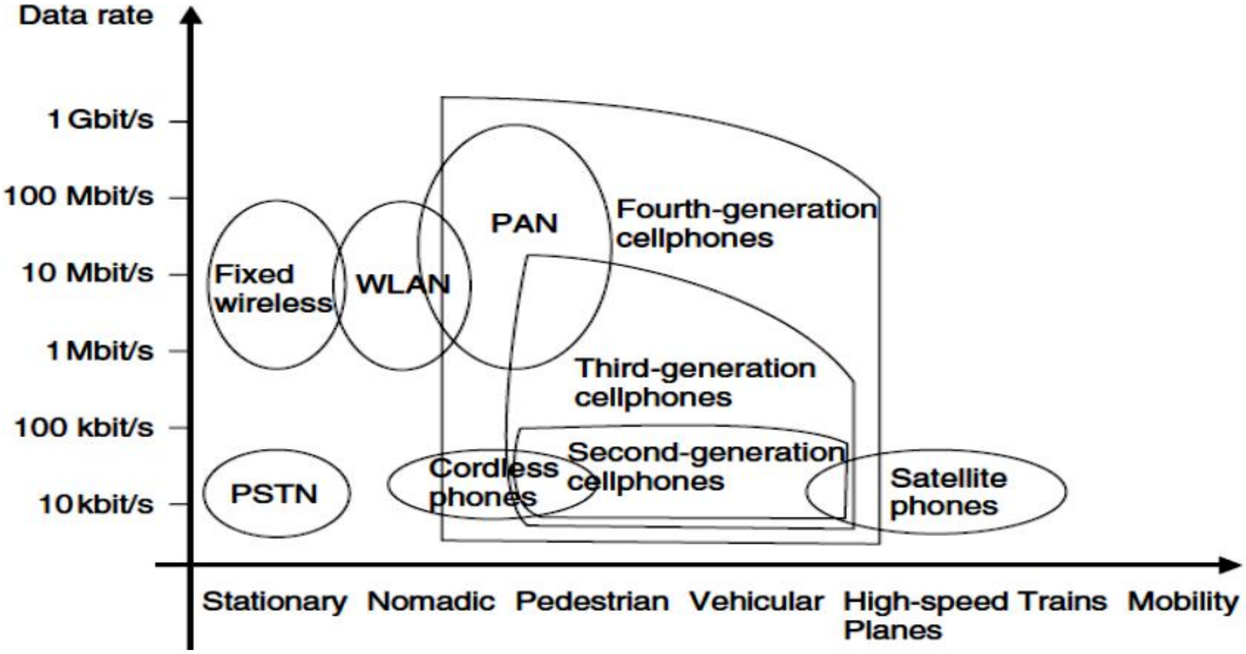


Figure 2.2 data rate versus mobility for various applications [11]

2.2. Technical Challenges of Wireless Communications

2.2.1. Multipath Propagation

For wireless communications, the transmission medium is the radio channel between transmitter TX and receiver RX. The signal can get from the TX to the RX via a number of different propagation paths. In some cases, a Line Of Sight (LOS) connection might exist between TX and RX. Furthermore, the signal can get from the TX to the RX by being reflected at or diffracted by different Interacting Objects (IOs) in the environment: houses, mountains (for outdoor environments), windows, walls, etc. The number of these possible propagation paths is very large. Each of the paths has a distinct amplitude, delay (runtime of the signal), direction of departure from the TX, and direction of arrival; most importantly, the components have different phase shifts with respect to each other.

2.2.2. Fading

A simple RX cannot distinguish between the different Multi Path Components (MPCs); it just adds them up, so that they interfere with each other. The interference between them can be constructive or destructive, depending on the phases of the MPCs. The phases, in turn, depend mostly on the run length of the MPC. For this reason, the interference, and thus the amplitude of the total signal, changes with time if either TX or RX is moving. This effect – namely, the changing of the total signal amplitude due to interference of the different MPCs – is called small-scale fading. Even a small movement can result in a large change in signal amplitude. A similar effect is known to all owners of car radios – moving the car by less than 1m (e.g., in stop-and-go traffic) can greatly affect the quality of the received signal [11].

It is well known from conventional digital communications that for non-fading communications links, the BER decreases approximately exponentially with increasing Signal-to-Noise Ratio (SNR) if no special measures are taken. However, in a fading channel, the SNR is not constant; rather, the probability that the link is in a fading dip (i.e., location with low SNR) dominates the behavior of the BER. For this reason, the average BER decreases only linearly with increasing average SNR [11].

Consequently, improving the BER often cannot be achieved by simply increasing the transmit power. Rather more sophisticated transmission and reception schemes have to be used. Due to fading, it is almost impossible to exactly predict the received signal amplitude at specific locations. For many aspects of system development and deployment, it is considered sufficient to predict the mean amplitude and the statistics of fluctuations around that mean.

2.2.3. Inter - symbol Interference

The runtimes for different MPCs are different. It is already mentioned above that this can lead to different phases of MPCs, which lead to interference in narrowband systems. In a system with large bandwidth, and thus good resolution in the time domain, the major consequence is signal dispersion: in other words, the impulse response of the channel is not a single delta pulse but rather a sequence of pulses (corresponding to different MPCs), each of which has a distinct arrival time in addition to having a different amplitude and phase. This signal dispersion leads to Inter-Symbol Interference (ISI) at the Rx. MPCs with long runtimes, carrying information from bit k, and MPCs with short runtimes, carrying contributions from bit k + 1 arrive at the Rx at the same time, and interfere with each other. Assuming that no special measures are taken, this ISI leads to errors that cannot be eliminated by simply increasing the transmit power, and are therefore often called irreducible errors. ISI is essentially determined by the ratio between symbol duration and the duration of the impulse response of the channel. This implies that ISI is not only more important for higher data rates but also for multiple access methods that lead to an increase in transmitted peak data rate. Finally, it is also noteworthy that ISI can even play a role when the duration of the impulse response is shorter (but not much shorter) than bit duration.

2.2.4. Spectrum Limitations

The spectrum available for wireless communications services is limited, and regulated by international agreements. For this reason, the spectrum has to be used in a highly efficient manner. Two approaches are used: **regulated** spectrum usage, where a single network operator has control over the usage of the spectrum, and **unregulated** spectrum, where each user can transmit without additional control, as long as (s)he complies with certain restrictions on the emission power and bandwidth.

2.2.5. Assigned Frequencies

The frequency assignment for different wireless services is regulated by the International Telecommunications Union (ITU), a sub-organization of the United Nations. In its tri-annual conferences (World Radio Conferences), it establishes worldwide guidelines for the usage of spectrum in different regions and countries. Further regulations are issued by the frequency regulators of individual countries, including the Federal Communications Commission (FCC) in the U.S.A., the Association of Radio Industries and Businesses (ARIB) in Japan, and the European Conference of Postal and Telecommunications Administrations (CEPT) in Europe [11] and Ethiopian Broadcast Authority in Ethiopia. While the exact frequency assignments differ, similar services tend to use the same frequency ranges all over the world:

- ✓ Below 100 MHz: these frequencies are Citizens' Band (CB) radio, pagers, and analog cordless phones.
- ✓ 100–800 MHz: these frequencies are mainly used for broadcast (radio and TV) applications.
- ✓ 400–500 MHz: a number of cellular and trunking radio systems make use of this band. It is mostly systems that need good coverage, but show low user density.

- ✓ 800–1000 MHz: several cellular systems use this band (analog systems as well as second generation cellular). Also some emergency communications systems (trunking radio) make use of this band.
- ✓ 1.8–2.1 GHz: this is the main frequency band for cellular communications. The current (second generation) cellular systems operate in this band, as do most of the third-generation systems. Many cordless systems also operate in this band.
- ✓ 2.4–2.5 GHz: the Industrial, Scientific, and Medical (ISM) band. Cordless phones, Wireless Local Area Networks (WLANs) and wireless Personal Area Networks (PANs) operate in this band; they share it with many other devices, including microwave ovens.
- ✓ 3.3–3.8 GHz: is envisioned for fixed wireless access systems.
- ✓ 4.8–5.8 GHz: in this range, most WLANs can be found. Also, the frequency range between5.7 and 5.8 GHz can be used for fixed wireless access, complementing the 3-GHz band. Also car-to-car communications are working in this band.
- ✓ 11–15 GHz: in this range are the most popular satellite TV services, which use 14.0–14.5 GHz for the uplink, and 11.7–12.2 GHz for the downlink.

2.2.6. Limited Energy

Truly wireless communications requires not only that the information is sent over the air (not via cables) but also that the RX is powered by one-way or rechargeable batteries. Otherwise, the TX would be tied to the "wire" of the power supply, batteries in turn impose restrictions on the power consumption of the devices. The requirement for small energy consumption results in several technical imperatives:

- ➢ Signal processing must be done in an energy-saving manner. This restriction has important consequences for the algorithms that can be used for interference suppression, combating of ISI, etc.
- ➢ The RX needs to have high sensitivity. For example, Global System for Mobile Communications (GSM) is specified so that, even a received signal power of -100dBm leads to an acceptable transmission quality. But the high requirements on RX sensitivity have important consequences for the construction of the RX (low-noise amplifiers,

sophisticated signal processing to fully exploit the received signal) as well as for network planning.

- Maximum transmit power should be used only when required. If the RX is close to the TX, and thus the channel has only a small attenuation, transmit power should be kept low.
- For cellular phones, and even more so for sensor networks, an energy-efficient “standby” or “sleep” mode has to be defined.

2.3. Railways and wireless communication

Advancement in communication technology makes possible to apply wireless communication techniques in almost all sectors for the transmission of information in all forms between any two points. Wireless communication system finds a very promising role in railway transportation system as it can reduce the maintenance and inspection requirements of railway systems while maintaining safety and reliability. Since in this modern age, railway infrastructure is developing very rapidly. So to accommodate the requirements of growing system past wired communication systems for signalling and data transfer is replaced by latest wireless communication systems. The requirements of an efficient railway communication network can be illustrated as [9]:

- It provides uninterrupted communication between drivers and signalers at any time any place.
- Drivers get alerts about any potential hazards well before in time.
- In an emergency, drivers can communicate quickly with signalers and control station.
- Signalers are aware about the location of train on the track.
- It should reduce the incidents of faulty signalling and failure to control the train.
- Timely and accurate information about train schedule should be available to the passengers.

When trains run on railway tracks they follow rules of operations in which safety plays a very important role. The most important rule in respect of safety is ensuring that two trains do not occupy the same position on the track at the same time [12]. To make this rule work operation of trains uses signalling to control movement of trains on tracks and divides tracks into several sections which are protected by the signals. Simultaneously the drivers maintain contact with controller for updating the traffic status and possible changes in route. Signalling and communication technologies developing continue and providing safer, faster mode of information exchange.

2.3.1. Communication and signalling systems for railway control

Maintaining Safe distance between trains is the most important safety precaution for railway transportation. This safe distance is decided by the current train location, its relative speed to other trains in the same area, and the other trains locations and directions of movement. A large number of signalling strategies have been developed over the past years, to maintain the safety. Some of the current methods of signalling and train control systems are [9], [20] and [21]:

- Communications-Based Train Control (CBTC) Systems
- Advanced Train Control Systems (ATCS)
- Command Control and Communications Systems (CCCS)
- Incremental Train Control Systems (ITCS)
- Positive Train Control (PTC),
- Positive Train Separation (PTS)
- European Train Control System (ETCS)
- Global System for Mobile communications version for the rail industry (GSM-R)
- Terrestrially Trunked Radio (TETRA)
- Enhanced position and location reporting system (EPLRS)

2.4. Summary

The aim has been to ensure the safety of people and trains and to meet schedules, in other words, to ensure the railway service under secure conditions. To achieve this it has been necessary to establish a communication channel between the mobile elements (trains, infrastructure repair machinery, towing or emergency vehicle, and so on) and the earth fixed elements (command posts and stations, signals, tracks, etc.).

Chapter 3

WIRELESS COMMUNICATION INSIDE RAILWAY TUNNEL

3.1. Introduction

A great deal of work is being done to optimize the performances of digital wireless communication systems, and most of the effort is focused on the urban environment where technologies evolve surprisingly fast. Deployment of new emerging technologies, all based on digital communications, first requires the knowledge of the physical layer in order to develop efficient antenna design and communication algorithms. Tunnels, including rail, road and pedestrian tunnels, even if they do not represent a wide coverage zone, must be taken into account in the network architecture. In order to cover the tunnel, two solutions have traditionally been proposed: the so-called “natural propagation” using antennas of small size, and leaky coaxial cables. However, the implementation of radiating cables is expensive, because the diameter of the cable must be large enough to avoid a prohibitive attenuation in the 1-5 GHz band [41]. The focus of this thesis is on a link based on natural propagation.

Railway tunnels are very critical and important part of the railway track as safety requirement increases, when a train passes through the tunnels. In such cases, fast and reliable mode of communication is needed, as previously discussed that at present wired communication has totally replaced by the wireless communication system. To develop a setup of wireless communication system for tunnel it is necessary to study about the radio wave propagation in tunnel. Natural propagation of electromagnetic waves is the simplest method to establish a radio link in an underground tunnel. Nowadays, the problem of radio communication in tunnels has found solutions using leaky transmission lines as supports for propagation of transverse electromagnetic modes. These modes are characterized by the fact that there is no cut-off frequency, and by an attenuation which increases with increasing frequency. However, when the frequency is high enough, natural propagation modes, which are transverse electric or transverse magnetic, can appear and interfere with the transmission line-supported transverse electromagnetic modes [25].

ERC is going to implement the following railway tunnel at piassa (Giyorgis) with stated dimension and shape shown below

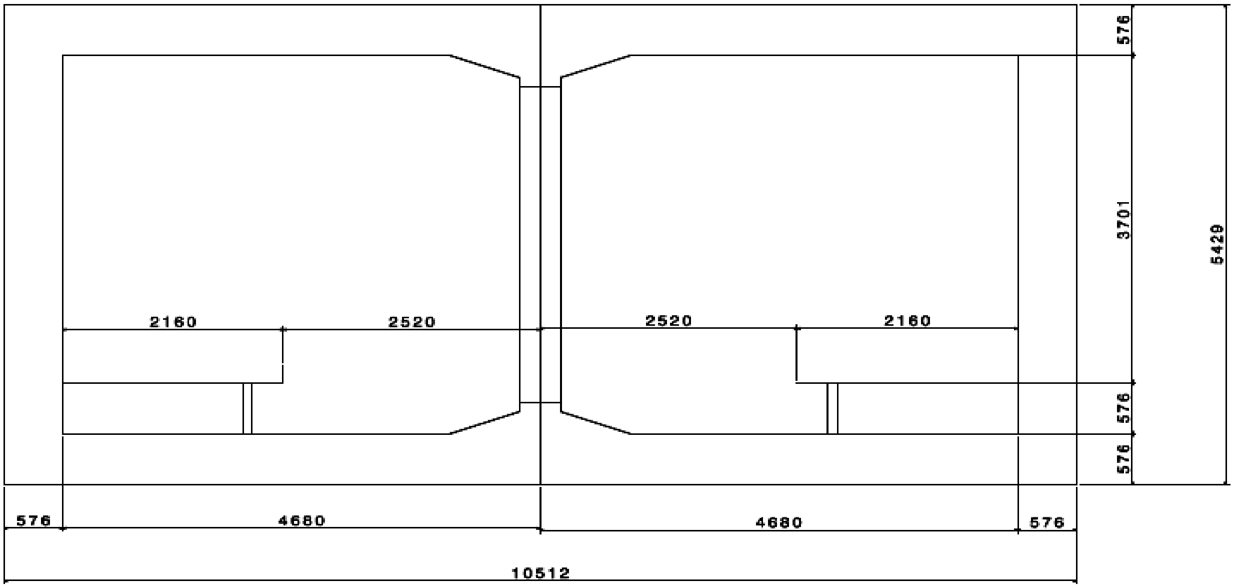


Figure 3.1 structural shape of open-cut station (Underground one-story side platform station) [30]

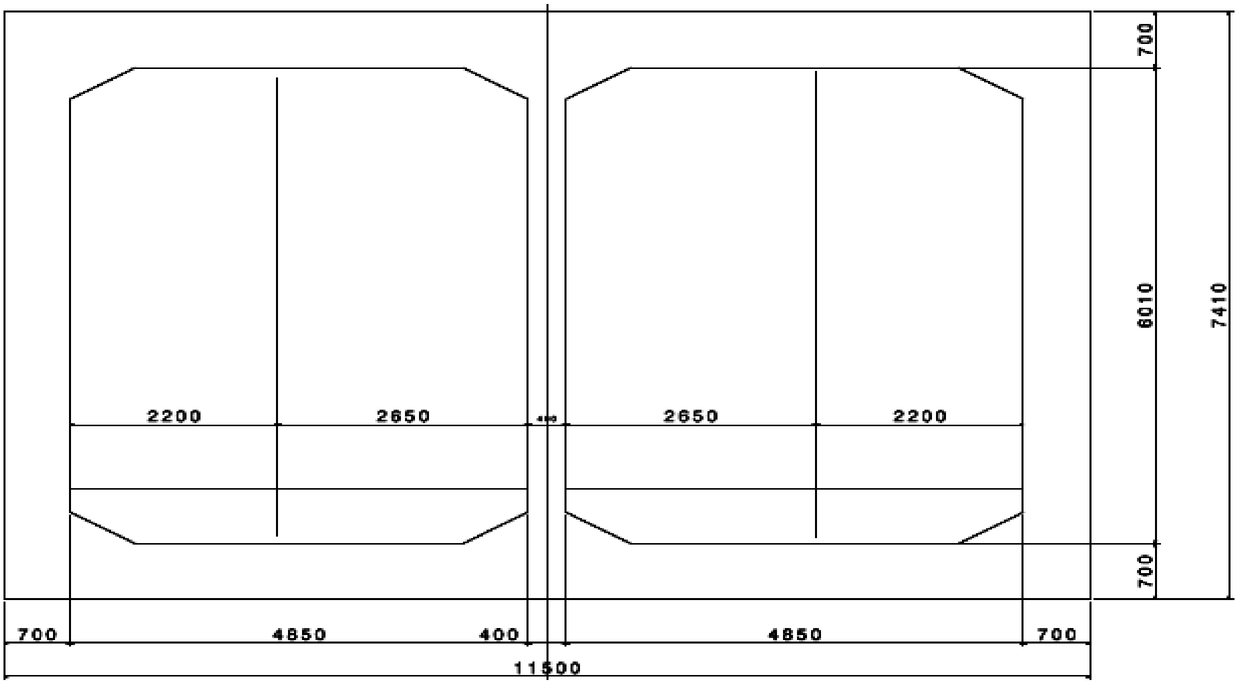


Figure 3.2 structural cross section of open-cut tunnel (Structural cross section form of open-cut section) [30]

Tunnels can be considered as hollow conductors which will work as a waveguide. Waveguides are the guided transmission lines in which wave travels by using the phenomena of total internal reflection. Waves travels through waveguide in transverse electric or transverse magnetic modes only when frequency is higher than a certain cut-off frequency. The values of these cut-off frequencies depend on the given mode, and are also determined by the shape and the transverse dimension of the gallery. Expression for cut-off wavelength for rectangular waveguide (as here is considered the rectangular tunnel), is

$$\lambda_{mn} = \frac{2\sqrt{ab}}{\sqrt{m^2\left(\frac{b}{a}\right) + n^2\left(\frac{a}{b}\right)}}$$

Where **a** is the width of the guide and **b** is the height, and m, n are the integers decides the mode of propagation. Its values are 1, 2, 3… for the TM_{mn} modes, and equal to 0, 1, 2, 3, for the TE_{mn} modes.

3.2. Modeling the tunnel as propagation channel

Many approaches have been developed to theoretically study electromagnetic wave propagation inside a tunnel, the most well-known being those based either on the ray theory or on the modal theory (Mahmoud, 1988; Dudley et al., 2007). The transmitting frequency range must be chosen such that the attenuation per unit length is not prohibitive. To fulfill this requirement, the tunnel must behave as an oversized waveguide. Consequently, the wavelength must be much smaller than the transverse dimensions of the tunnel, which leads to transmitting frequencies greater than few hundred MHz in usual road or train tunnels [18].

3.3. Wave guide and antenna

Waveguides are used to transfer electromagnetic power efficiently from one point in space to another. Some common guiding structures are shown in the figure below. In practice, the choice of structure is dictated by: (a) the desired operating frequency band, (b) the amount of power to be transferred, and (c) the amount of transmission losses that can be tolerated.

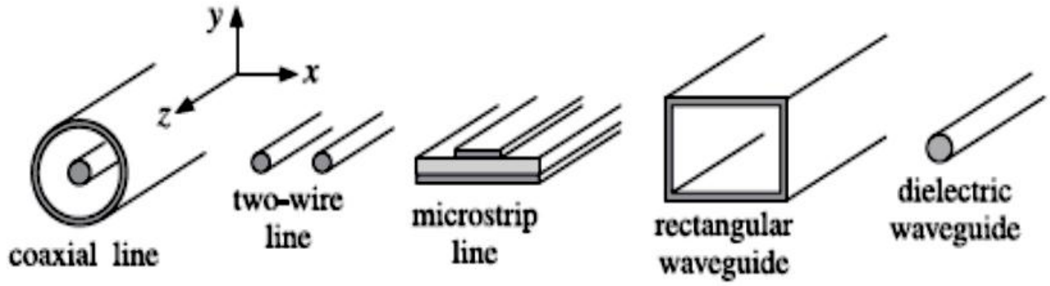


Figure 3.3 wave guide structures

Coaxial cables are widely used to connect RF components. Their operation is practical for frequencies below 3 GHz [18], and above that the losses are too excessive. For example, the attenuation might be 3 dB per 100 m at 100 MHz, but 10 dB/100 m at 1 GHz, and 50 dB/100 m at 10 GHz. Their power rating is typically of the order of one kilowatt at 100 MHz, but only 200 W at 2 GHz, being limited primarily because of the heating of the coaxial conductors and of the dielectric between the conductors (dielectric voltage breakdown is usually a secondary factor.) However, special short-length coaxial cables do exist that operate in the 40 GHz range [18]. Another issue is the single-mode operation of the line. At higher frequencies, in order to prevent higher modes from being launched, the diameters of the coaxial conductors must be reduced, diminishing the amount of power that can be transmitted. Two-wire lines are not used at microwave frequencies because they are not shielded and can radiate. One typical use is for connecting indoor antennas to TV sets. Rectangular waveguides are used routinely to transfer large amounts of microwave power at frequencies greater than 3 GHz. For example at 5 GHz, the transmitted power might be one megawatt and the attenuation only 4 dB/100 m. Optical fibers operate at optical and infrared frequencies, allowing a very wide bandwidth. Their losses are very low, typically, 0.2 dB/km. The transmitted power is of the order of milliwatts.

Where it is defined the so-called cutoff wave number k_c by:

$$K_c^2 = \omega^2 \epsilon\mu - \beta^2 = \frac{\omega^2}{c^2} - \beta^2 = k^2 - \beta^2$$

Cut off wavelength and freq.

$$\omega_c = ck_c , \qquad \lambda_c = \frac{2\pi}{k_c}$$

3.3.1. Rectangular Waveguides

Next, is detailed discussion of a rectangular hollow waveguide with conducting walls, as shown in Figure below. Without loss of generality, it may be assumed that the lengths **a**, **b** of the inner sides satisfy $b \le a$. The guide is typically filled with air, but any other dielectric material ε, μ may be assumed.

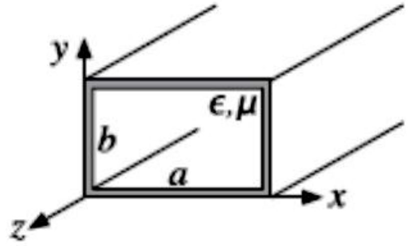


Figure 3.4 rectangular wave guide

The simplest and dominant propagation mode is the so-called TE_{10} mode and depends only on the x-coordinate (of the longest side.) Therefore, begin by looking for solutions that depend only on x. In this case, the Helmholtz equation reduces to:

$$\partial_x^2 H_z(x) + k_c^2 H_z(x) = 0$$

The most general solution is a linear combination of cos $k_c x$ and sin $k_c x$. However, only the former will satisfy the boundary conditions. Therefore, the solution is:

$$H_z(x) = H_0 cos k_c x$$

Where H_0 is a (complex-valued) constant. Because there is no y-dependence, that $\partial yHz= 0$, and hence $H_y = 0$ and $E_x = 0$. It also follows that:

$$H_x(x) = -(j\beta/k^2_c)\partial x\ Hz = -(j\beta/k^2_c)(-k_c)H_0 \sin k_c x = (j\beta/k_c)H_0 \sin k_c x \equiv H_1 \sin k_c x$$

Then, the corresponding electric field will be:

$$E_y(x) = -\eta_{TE} H_x(x) = -\eta_{TE}(j\beta/k_c)H_0 \sin k_c x \equiv E_0 \sin k_c x$$

where constants defined by:

$$H_1 = (j\beta/kc)H_0$$

$$E_0 = -\eta_{TE} H_1 = -\eta_{TE}(j\beta/k_c)H_0 = -j\eta(\omega/\omega_c)H_0$$

where $\eta_{TE} = \eta\omega/\beta c$ is used. In summary, the non-zero field components are

$H_z(x) = H_0 \cos k_c x$ $H_x(x) = H_1 \sin k_c x$ $E_y(x) = E_0 \sin k_c x$	=	$H_z(x, y, z, t) = H_0 \cos k_c x e^{j\omega t - j\beta z}$ $H_x(x, y, z, t) = H_1 \sin k_c x e^{j\omega t - j\beta z}$ $E_y(x, y, z, t) = E_0 \sin k_c x e^{j\omega t - j\beta z}$

Assuming perfectly conducting walls, the boundary conditions require that there be no tangential electric field at any of the wall sides. Because the electric field is in they-direction, it is normal to the top and bottom sides. But, it is parallel to the left and right sides. On the left side, $x = 0$, $E_y(x)$ vanishes because $\sin k_c x$ does. On the right side, $x = a$, the boundary condition requires:

$$E_y(a) = E_0 \sin k_c a = 0 \Rightarrow \sin k_c a = 0$$

This requires that $k_c a$ be an integral multiple of π:

$$k_c a = n\pi \Rightarrow k_c = (n\pi/a)$$

These are the so-called TE_{n0} modes. The corresponding cutoff frequency $\omega_c = ck_c$,

$f_c = \omega_c/2\pi$, and wavelength $\lambda_c = 2\pi/k_c = c/f_c$are:

$$\omega_c = (cn\pi/a), \quad f_c = (cn/2a), \quad \lambda_c = (2a/n) \quad \rightarrow \quad (TE_{n0} \text{ modes})$$

The dominant mode is the one with the lowest cutoff frequency or the longest cutoff wavelength, that is, the mode TE_{10} having $n = 1$. It has:

$$k_c = (\pi/a), \quad \omega_c = (c\pi/a), \quad f_c = (c/2a), \quad \lambda_c = 2a \quad \rightarrow \quad (TE_{10} \text{ mode})$$

Figure below depicts the electric field

$$E_y(x) = E_0 \sin k_c x = E_0 \sin(\pi x/a)$$

of this mode as a function of x.

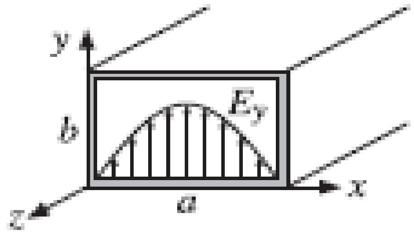


Figure 3.5 Electric field inside a rectangular waveguide

3.3.2. Operating Bandwidth

All wave guiding systems are operated in a frequency range that ensures that only the lowest mode can propagate. If several modes can propagate simultaneously, one has no control over which modes will actually be carrying the transmitted signal. This may cause undue amounts of dispersion, distortion, and erratic operation. A mode with cutoff frequency ω_c will propagate only if its frequency is $\omega \geq \omega_c$, or $\lambda < \lambda_c$. If $\omega < \omega_c$, the wave will attenuate exponentially along the guide direction. This follows from the ω, β relationship:

$$\omega^2 = \omega^2 c + \beta^2 c^2 \Rightarrow \quad \beta^2 = \frac{\omega^2 - \omega^2 c}{c^2}$$

If $\omega \geq \omega_c$, the wave number β is real-valued and the wave will propagate. But if $\omega < \omega_c$, β becomes imaginary, say, $\beta =-j\alpha$, and the wave will attenuate in the **z** direction, with a penetration depth **δ**= 1/α:

$$e^{-j\beta z}=e^{-\alpha z}$$

If the frequency ω is greater than the cutoff frequencies of several modes, then all of these modes can propagate. Conversely, if ω is less than all cutoff frequencies, then none of the modes can propagate. If the cutoff frequencies are arranged in increasing order, $\omega_{c1} < \omega_{c2} < \omega_{c3} < \cdots$, then, to ensure single-mode operation, the frequency must be restricted to the interval $\omega_{c1} < \omega < \omega_{c2}$, so that only the lowest mode will propagate. This interval defines the operating bandwidth of the guide. These remarks apply to all wave guiding systems, not just hollow conducting waveguides [18].

For example, in coaxial cables the lowest mode is the TEM mode having no cutoff frequency, $\omega_{c1}= 0$. However, TE and TM modes with non-zero cutoff frequencies do exist and place an upper limit on the usable bandwidth of the TEM mode. Similarly, in optical fibers, the lowest mode has no cutoff, and the single-mode bandwidth is determined by the next cutoff frequency.

In rectangular waveguides, the smallest cutoff frequencies are:

$$f_{10} = c/2a, \quad f_{20} = c/a = 2f_{10}, \text{ and } \quad f_{01} = c/2b$$

Because it is assumed that $b \leq a$, it follows that always $f_{10} \leq f_{01}$.

If

$$b \leq \frac{a}{2}, \text{ then } \frac{1}{a} \leq \frac{1}{2b} \text{ and}$$

Therefore,

$$f_{20} \leq f_{01},$$

So that the two lowest cutoff frequencies are f_{10} and f_{20}. On the other hand,

If

$$\frac{a}{2} \leq b \leq a,$$

Then

$$f_{01} \leq f_{20}$$

And the two smallest frequencies are f_{10} and f_{01} (except when b = a, in which case $f_{01}= f_{10}$ and the smallest frequencies are f_{10} and f_{20}).It is evident from this figure that in order to achieve the widest possible usable bandwidth for the TE_{10} mode, the guide dimensions must satisfy $b \leq \frac{a}{2}$ so that the bandwidth is the interval $[f_c, 2f_c]$, where $f_c = f_{10}= c/2a$. In terms of the wavelength $\lambda = \frac{c}{f}$, the operating bandwidth becomes:

$$0.5 \leq \frac{a}{\lambda} \leq 1, \text{ or, } \quad a \leq \lambda \leq 2a.$$

At the total amount of transmitted power in this mode is proportional to the cross-sectional area of the guide, **ab**. Thus, if in addition to having the

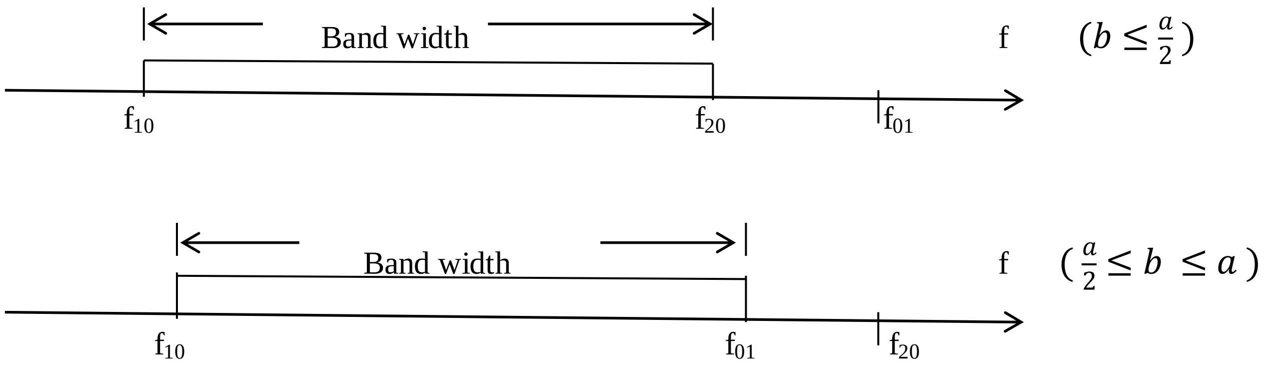


Figure 3.6 Operating bandwidth in rectangular waveguides

Widest bandwidth, it is also required to have the maximum power transmitted, the dimension **b** must be chosen to be as large as possible, that is, $b = \frac{a}{2}$. Most practical guides follow these side proportions. If there is a "canonical" guide, it will have $b = \frac{a}{2}$ and be operated at a frequency that lies in the middle of the operating band [f_c, $2f_c$], that is,

$$f = 1.5fc = 0.75\left(\frac{c}{a}\right)$$

3.3.3. Radio wave propagation mechanisms in wave guide

The basic radio propagation mechanisms include reflection, refraction and diffraction. From the radio propagation perspective, the effect of a medium can be determined by three parameters: conductivity σ, permittivity ε and permeability μ. These three parameters are known as the constitutive parameters of the medium [41]. In lossless media, when a plain wave propagates from a medium with permittivity ε_1 and permeability μ_1 to another medium with different permittivity ε_2 and permeability μ_2, reflection and refraction will happen at the boundary of these two media. The two produced reflection and refraction waves have exactly the same frequency as the incident wave. The directions of the two waves follow the Snell's law of reflection and the Snell's law of refraction, respectively, as follows

$$\theta_r = \theta_i \quad \text{Snell's reflection law}$$

$$\frac{sin\,\theta_r}{\sin\theta_i} = \frac{n1}{n2} \quad \text{Snell's refraction law}$$

Where θ_i, θ_r and θ_t are the incident angle, reflection angle and refraction angle, respectively. The parameter **n** is the refractive index which depends on the relative permittivity ε_r and relative permeability μ_r of media according to:

$$n = \sqrt{\epsilon_r \mu_r}$$

The ε_r and μ_r are the medium's permittivity and permeability expressed relative to those of vacuum. Above, it is assumed that boundary or surface between the two media is a perfectly smooth surface. The reflection in this case is usually termed specular reflection. When the surface is getting rougher, there will be also an amount of scattered waves around the main reflection wave. Scattering is a special case of reflection, which describes the phenomenon that radio waves are reflected in many directions by irregular objects or rough surfaces.

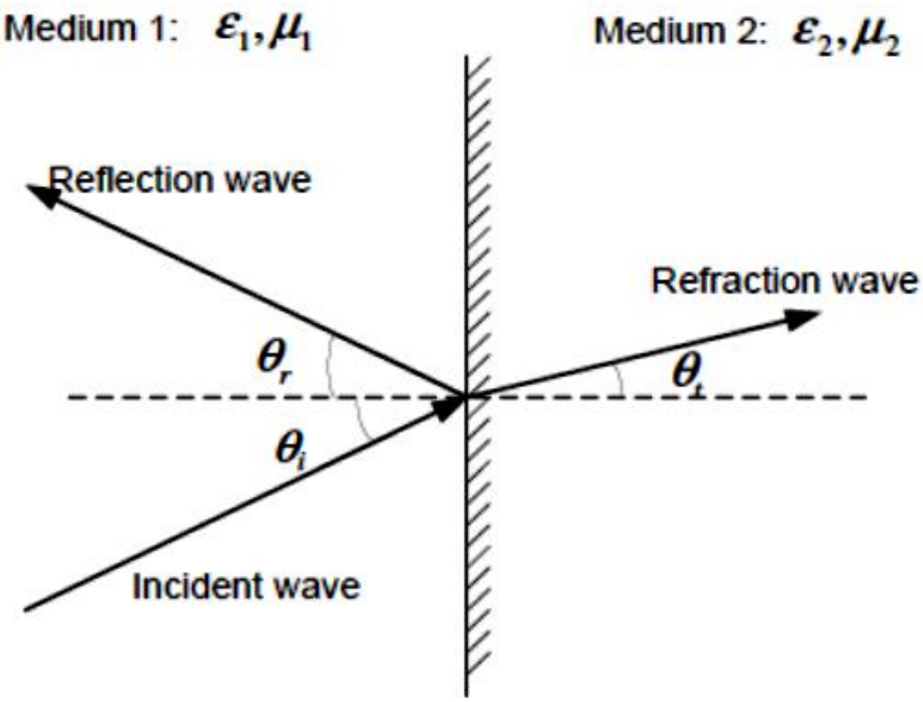
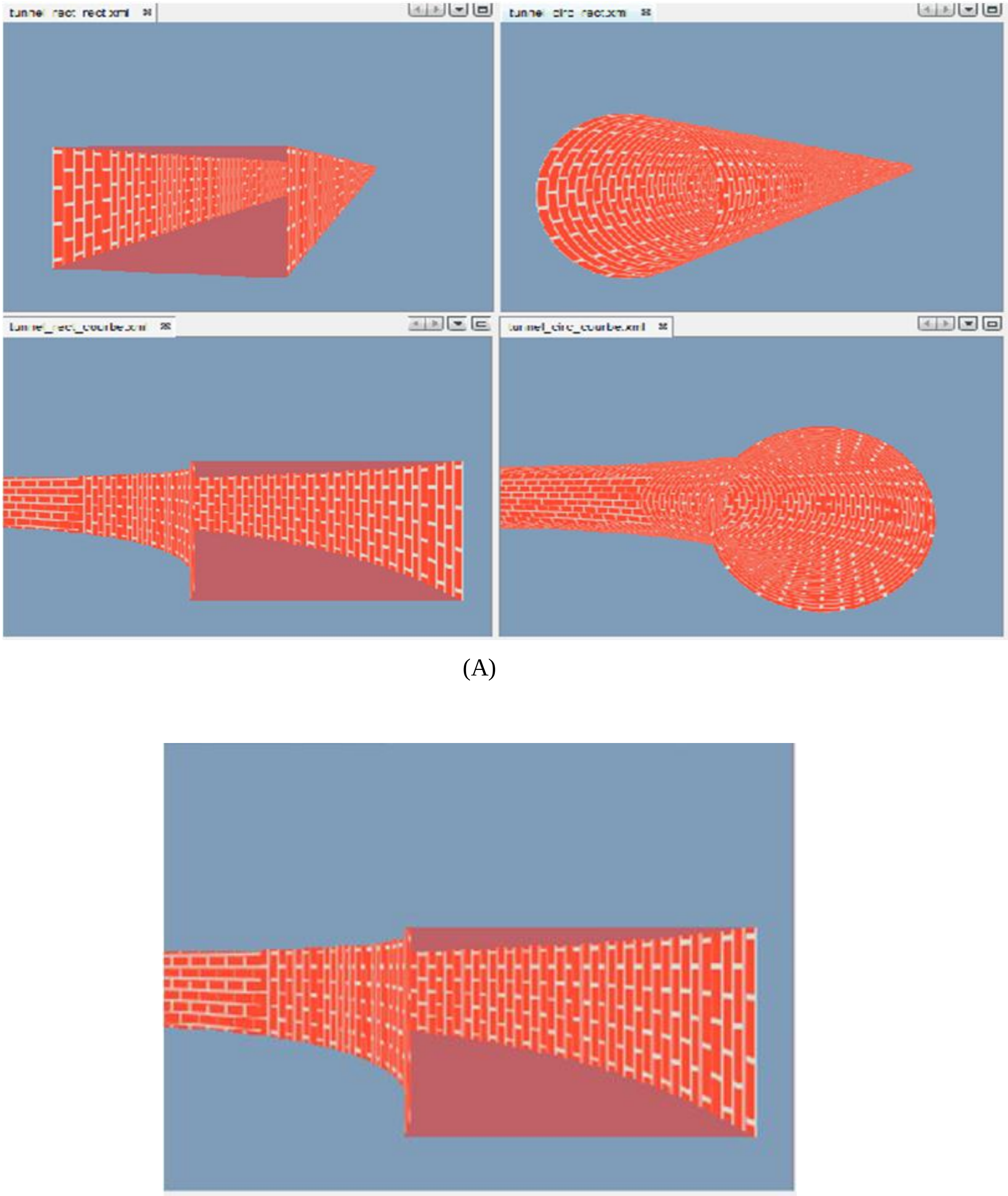


Figure 3.7 wave transmission principle inside wave guide



(A)

(B)

Figure 3.8 (A) Tunnel types mostly found in railway (B) Tunnel type for ERC AA-LRT at piassa

Since in the AA-LRT tunnel is UWB radio communication frequency range the wavelength is much smaller than the transversal dimensions of AA-LRT tunnel at piassa, tunnel propagation can be considered as in an oversized waveguide. This condition makes it possible to apply the asymptotic geometrical optics theory. Then, the tunnel can be modeled as a multipath channel with white Gaussian noise. In that case, it can be represented by the time variant channel given by

$$h(t,\tau) = \sum_{k=0}^{\mathrm{N(t)}-1} a_k(t)\delta[\tau - \tau_k(t)]e^{j\theta_k(t)}$$

Where a_k is the k^th^ path amplitude value, T_k is the arrival time of the k^{th} path, θ_k is the k^{th} path phase value, δ is the Dirac delta function, and N is the number of resolvable multi-paths. If the channel is supposed to be stable during the relevant periods, the time invariant version can be used. It is then expressed as a geometrical ray model for straight rectangular tunnels [41].

$$h(\tau) = \sum_{k=0}^{\mathrm{N}-1} a_k\delta[\tau - \tau_k]e^{j\theta_k}$$

3.4. Losses that exist when modelling of the channel

Propagation prediction and modeling of radio coverage inside a tunnel depend on the section, curves, and construction characteristics of the walls. Railway tunnels have special characteristics: ballast on the ground, variable semicircular section, overhead cables, construction in concrete, smooth curves, etc. The radio planning of the different tunnels of the new railway lines requires an accurate propagation model to be able to use it on the ground, combining measurements with simulations, in a railway environment where the taking of measurements is complex and expensive. The required calculations are principally oriented toward predicting the number of repeaters needed and their location inside the tunnel for a specification of signal level, tunnel geometry, curves, and fading margins. Basically, two techniques can be used to calculate the propagation inside a tunnel:

- Modal analysis and
- Ray-optical modeling

Both techniques have been widely used for tunnel propagation analysis; both methods are combined to calculate the propagation inside the tunnel. Modal analysis is used in straight tunnels and ray tracing is used to calculate extra attenuations in curves. the tunnel is considered as a waveguide only propagation of modes with frequencies higher than the tunnels cutoff frequency is possible. Due to the size of the tunnel, the cutoff frequency of the fundamental modes is very low (i.e., some Megahertz), therefore, at high frequencies a wide range of $E_{mn.}$ hybrid modes are found propagating inside the tunnels for a rectangular waveguide based model of the tunnel. Using modal theory the losses of horizontally and vertically polarized E_{mn} modes can be quantified applying modal analysis. Therefore the overall propagation attenuation at a distance z is computed as:

$$L(z) = \mathrm{L}_{\mathrm{ant}} + L_{\mathrm{mn}}^{\mathrm{v,h}}(z) + L_{\mathrm{roughness}}(z) + L_{tilt} + L_{curve}(z')$$

In the near field region the field amplitude suffers strong fading and rapid decreases resulting from the contribution of many rays propagating from different grazing angles with high losses. define a far field region can be defined, where the attenuation factor is smaller because it can be assumed that there is only one mode propagating through the tunnel. The ray tracing theory is used to compute the separation of the two propagation zones and then modal analysis can be applied to compute the propagation attenuation in both regions. $E_{mn}^{h}\ and\ E_{mn}^{v}$ modes are defined by the following phase relation:

$$\sin \varphi 1 = \frac{m\lambda}{2a}, \qquad m = 1,2,3, \dots$$

$$\sin \varphi 2 = \frac{n\lambda}{2b}, \qquad n = 1,2,3, \dots$$

Where $\varphi 1$ and $\varphi 2$ are the grazing angles of incidence of the rays with vertical and horizontal walls, respectively and **a** and **b** are the horizontal and vertical dimensions of the tunnel respectively. It can be assumed that the wave length **λ is** small in comparison with a and b and approximate the sine by its argument. The attenuation depends on the number of reflection of the rays, i.e., N_1 and N_2 and the reflection coefficient of the signal over the vertical and horizontal walls along the distance z. the number of reflections is obtained as:

$$N_1 \approx \frac{zm\lambda}{2a^2}$$

$$N_2 \approx \frac{zm\lambda}{2b^2}$$

With both N_1= 1and N_2 =1, the distance from the transmitter to the “breaking point” is defined by:

$$z_{NF} \approx \max(\frac{a^2}{\lambda},\frac{b^2}{\lambda})$$

z_{NF} is directly proportional to the square of the largest dimension of the tunnel and inversely proportional to the wave length therefore, from a transmitter to a distance Z_{NF}. It is considered that there are horizontally and vertically polarized E_{mn} modes. From Z_{NF} it can be considered that only E_{10}^{h} mode propagates.

3.4.1. Propagation attenuation

The signal propagating through the tunnel is made up of several modes that propagate with different attenuations. The bigger the tunnel section the smaller is the attenuation that is experienced by the modes propagating throughout the tunnel, because losses are inversely proportional to the cube of the height and width of the tunnel.

$$L_{mn}^{v,h}(z) = 10\,log_{10}\left[\sum_{i=1}^{m} * \sqrt{10^{2\alpha(i,j)^{h}z} + 10^{2\alpha(i,j)^{v}z}}\right] \quad dB$$

In addition to this losses are directly proportional to the square of the order of modes, so that higher modes experience stronger attenuation. Losses are also directly proportional to the square of the wavelength. Additional corrections to the model must be considered because of the roughness and tilt of the walls.

Roughness losses are particularly important in low frequencies and in old subway tunnels. In modern tunnels wall roughness is usually low. Tilt losses are more important in semicircular tunnels and must be adjusted carefully.

3.4.2. Effect of curvature on channel modelling

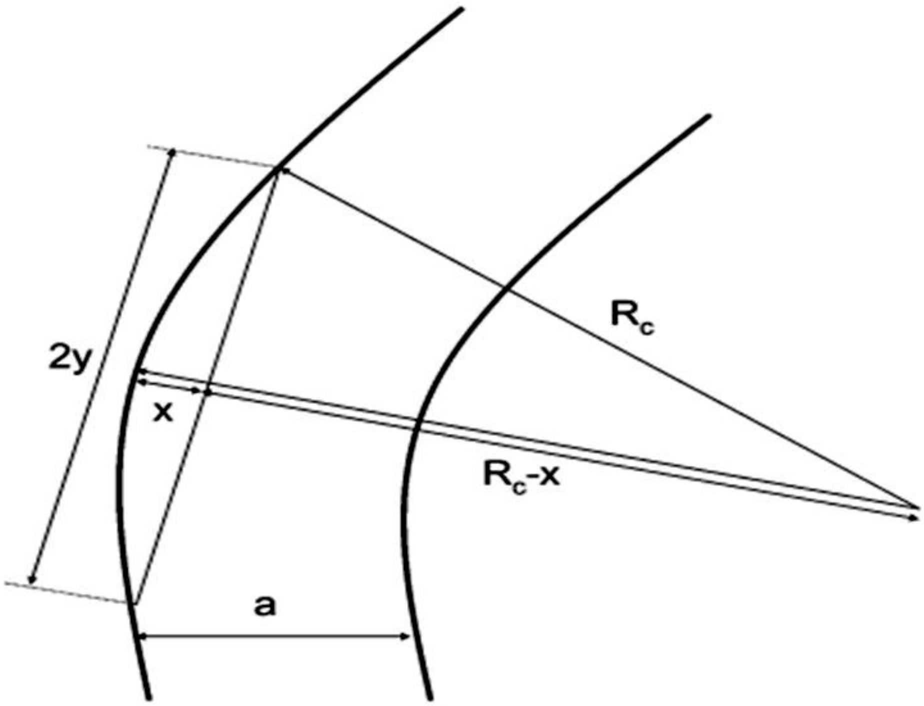


Figure 3.9 Geometry used to compute the attenuation of curves

To add more accuracy to the model, the waveguide model can be expanded, including losses for tunnel curves, to compute extra losses as a result of curves. The shooting and bouncing method is used. Basically, this method computes the attenuation considering the number of reflections in the vertical and horizontal walls. i.e., N_1 and N_2, and the reflection coefficients of vertical and horizontal walls, i.e., $\Gamma_1$and Γ_2.

For each ray of initial power P_0, the power P after $N_{1,2}$ reflections can be computed as:

$$\frac{p}{p_0} = [(/\Gamma_1/)^{2N_1} * (/\Gamma_2/)^{2\mathrm{N}_2}]$$

As tunnels usually only have curves on the horizontal axis, there are additional attenuations resulting from the increase in the number of reflections in the vertical walls. To compute the number of reflections in the vertical walls, it is defined that a curve section by using the radius of the curve R_c and the horizontal section of the tunnel a. The distance between the external wall of the tunnel and the ray that is launched along the tunnel width x. The value of y is defined by:

$$y = \sqrt{R_c^2 - (R_c - x)^2}$$

Now define φ1 as the grazing angle of incidence of the rays with the vertical walls, here consider a curved tunnel. Thus

$$\varphi_1 = tan^{-1}\left(\frac{\sqrt{R_c^2 - (R_c - x)^2}}{R_c - x}\right)$$

The attenuation of an electromagnetic wave (ray) inside the tunnel as a result of the curvature is considered as the average of the losses that are suffered by all the rays that are launched along the tunnel width a at a certain distance z'. Therefore, the attenuation that is suffered by a ray depends on the length of the curve, the reflection coefficient, and the roughness of the walls.

Considering these parameters, the extra attenuation resulting from a curve of length z, can be computed as:

$$L_{curv}(z') = 10 * (log_{10}[(\rho|\Gamma|)^{2zN_{1c}}])$$

Where ρ is the coefficient that considers the roughness of the walls, i.e.,

$$\rho = \exp\left(-2\left(\frac{2\pi h \sin(\varphi_1)}{\lambda}\right)^2\right)$$

where φ1 the angle of incidence with respect to the reflection surface, and h is the average square roughness of the walls.

The reflection coefficient of each ray Γ is computed using Fresnel's formulas and its value depends on the polarization. For vertical polarization it is must to use:

$$\Gamma = \Gamma_v = \frac{\varepsilon_{r_1}^* \sin(\varphi_1) - \sqrt{\sin^2\varphi_1 + \varepsilon_{r_1}^* - 1}}{\varepsilon_{r_1}^* \sin(\varphi_1) + \sqrt{\sin^2\varphi_1 + \varepsilon_{r_1}^* - 1}}$$

Whereas for horizontal polarization, it is must to use:

$$\Gamma = \Gamma_h = \frac{\sin(\varphi_1) - \sqrt{\sin^2\varphi_1 + \varepsilon^*_{r_1} - 1}}{\sin(\varphi_1) + \sqrt{\sin^2\varphi_1 + \varepsilon^*_{r_1} - 1}}$$

The permittivity is a complex number that is made up of the dielectric constant and the conductivity of the tunnel walls. i.e.,

$$\varepsilon^*_{r_1} = \varepsilon_{r_1} - j\frac{\sigma}{\omega\varepsilon_0}$$

In modern concrete tunnels it is possible to consider the conductivity of the walls as low; therefore, the effect of reflection coefficient is negligible, and the permittivity can be considered as real. All of the expressions have been defined for vertical surfaces and they are also applicable to horizontal surfaces. With these equations it is possible to compute the attenuation of curve of length z'. First modal analysis is applied to compute the propagation attenuation along the tunnels and then on the curved zones.

3.4.3. The near shadowing effect due to the presence of train

The essence of the near shadowing phenomenon [46] is that the line of sight (LOS) or the first Fresnel zone between transmitter (Tx) and receiver (Rx) is (partially) blocked by the user itself. This is why such effect is clearly observed in the cases when the user is relatively large, such as long trains in subway tunnel [46], but does not app ear in the cases when the user is very small compared with the tunnel. Thus, the relation between the size of the user and the size of the tunnel should be considered.

In the near shadowing zone, the final effect (of the combination of the shadowing effect owing to the large-size user and the multi-path propagation resulting from the tunnel walls) is very complex to be accurately depicted theoretically, but can be observed in the measurements and easily reproduced by the empirical model extracted from measured results. Hence, an empirical model is established for the path loss and shadow fading in the near shadowing zone [47].

When the train is passing in front of the Tx, the received signal power suffers a deep fading, and the propagation has strong multi-path. We call this phenomenon near shadowing.

Since in the real systems, antennas are directive, so it is very difficult to get the LOS with the Tx when the train is passing, even if the antennas are located in the upper part of the train.

The analysis of effect of train on the electromagnetic wave propagation inside tunnel

- This is the signal shadowing resulting from the blocking effects of two or more trains passing inside the tunnel. The problematic situation could be that a train stopped inside the tunnel could block the communication of other train.
- To understand this effect, as there are two tracks inside the tunnel there should be two transmitters with different frequencies serving for each track and considering two trains one on each track and testing for conditions when one of the train is at the center between the repeaters & its effect on the other train. The other case is when one train is close to the transmitter and its effect on the other train.
- For proper analysis there should be a field measurement taking place (not the scope of this thesis and because the railway is note functional yet) to carry out the measurement what needed is to let one of the train, the one with measuring equipment, to be stopped (stationary) at the middle of the repeaters (for the first case) and close to the transmitter (for the second case) on one track and the other is moving on the other track inside the tunnel.
- When the moving train passed the stationary train, a fade in the signal level is appreciated that is received from both transmitters.
- The moving train first blocks the front transmitter, and when it passes the stationary train it blocks the rear transmitter.
- The length of the shadowing case is dependent on the length and height of the train and the duration depends on the speed of the moving train;
- Different researchers try to measure the effect of a train inside the tunnel on communication of the other train and in reference [46] it is indicated that, about 15-20 dB variation will occur due to the shadowing effect. But this cannot be the case for this thesis as this thesis has its own environment which needs its own tunnel & train dimensions and field measurement, which is not the scope of this thesis.

These entire phenomenon can be reduced to $\pm 5\,dB$ when Isofrequency transmitters are used [46].

3.4.3.1. Critical Condition of the Near Shadowing Phenomenon and Distinction of Large-size User and Small-size User

The essence of the near shadowing phenomenon is that the first Fresnel zone, especially the 60% of the first Fresnel zone is blocked by the vehicle itself. Hence, the critical condition of the near shadowing phenomenon can be given when the vertical distance between any point P on the LOS and the top of the vehicle is equal to the 60% of the radius of the first Fresnel zone. When $dP = \frac{l_v}{2}$, the complete version of the critical condition can be simplified as $h_t + h_r - 2h = 0.6\sqrt{\lambda l_v}$, which indicates that even the widest part of the 60% of the first Fresnel zone is touched by the vehicle. Since the transmitting antenna is normally installed slightly under the top of the tunnel, and the receiving antenna is deployed on the vehicle, the critical condition can be finally simplified to be the relations among the wavelength, the height of the tunnel, and the height of the user. Correspondingly, when $H - h < 0.6\sqrt{\lambda l_v}$ is fulfilled, the user is classified as the large-size user, the near shadowing phenomenon should be considered in the network planning. Contrarily, when $H - h > 0.6\sqrt{\lambda l_v}$ is met, the user is defined as the small-size user, the near shadowing phenomenon does not exist. Where **H** is the height of the train and **h** is the height of the tunnel and $\mathbf{l_v}$ is the length of the train [47].

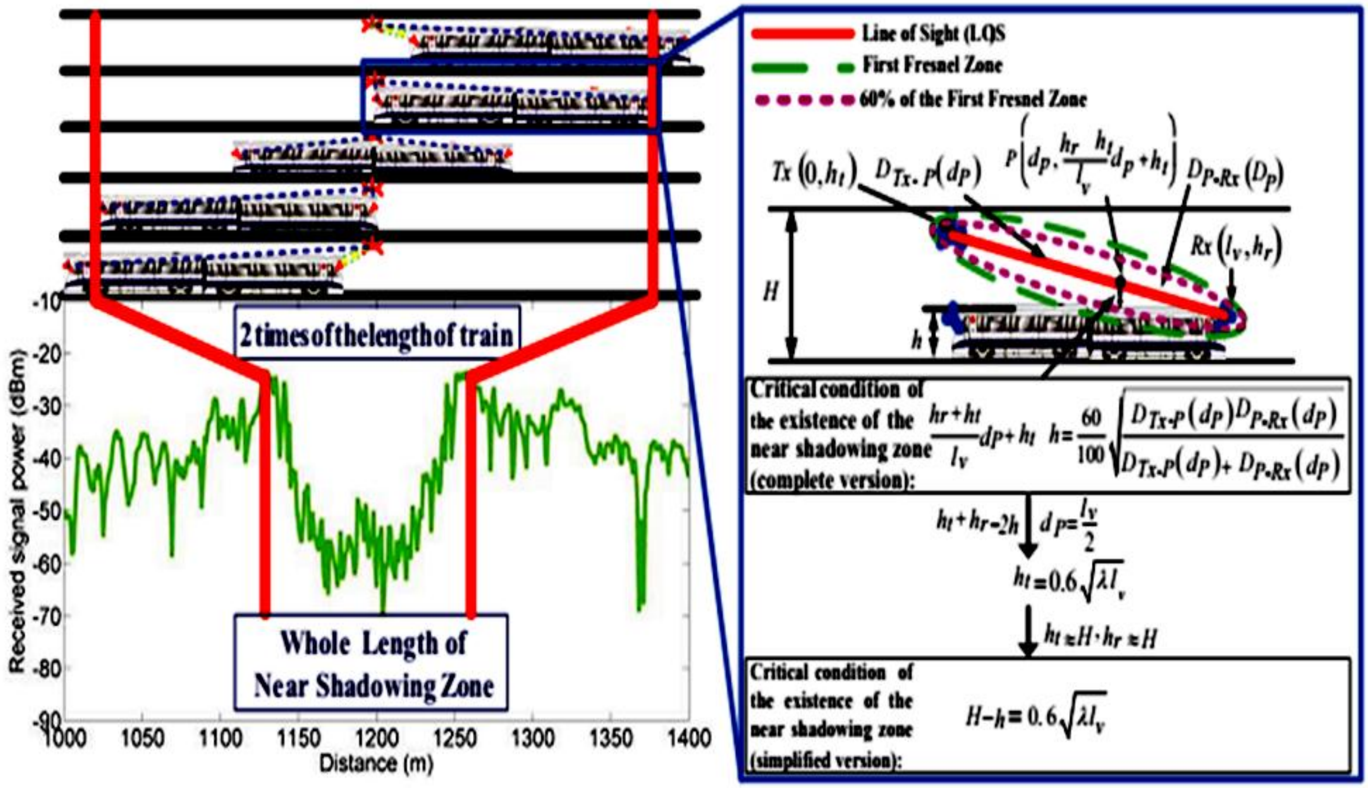


Figure 3.10 (a) Process of the near shadowing zone and the measured results in [46]; (b) sketch of the mechanism and the critical condition of the near shadowing phenomenon, where H and h denote the height of the tunnel and vehicle, respectively; λ denotes the wavelength; lv denotes the length of the vehicle [47].

It is noted that the near shadowing zone is not reflected in this case. This is because, $(H - h = 1.3 > 0.6\sqrt{\lambda l_v} = 0.7272$, which means that even though the absolute size of the train is not small; the train in this case (inside this tunnel and with this frequency) do not meet the condition of the large-size user. Thus, the near shadowing zone does not exist in this case.

3.4.4. The overall propagation attenuation

Considering the basic mode losses and roughness, tilt, and the curve coefficients that were defined, and predict propagation losses can be predicted with the distance using two different approaches, one for the near- field region and the other for the far-field region. The separation of regions is defined by the breaking point Z_{NF}. The following expressions provide a way of calculating the losses in decibels.

In the near field region, $Z < Z_{NF}$, consider losses of (m, n) modes as the RMS contribution of modes up to (10, 10) for both polarizations i. e.,

$$L(z) = \mathrm{L}_{\mathrm{ant}} + L_{\mathrm{mn}}^{\mathrm{v,h}}(z) + L_{\mathrm{roughness}}(z) + L_{tilt} + L_{curve}(z)$$

In the far- field region $Z > Z_{NF}$, only considered losses are at the first order (1, 0) vertical or horizontal mode that is

$$L(z) = \mathrm{L}_{\mathrm{ant}} + L_{10}^{\mathrm{v,h}}(z) + L_{\mathrm{roughness}}(z) + L_{tilt} + L_{curve}(z)$$

The model is easy to use, fast and accurate enough for radio planning in radio environment, very useful in predicting the location, number of repeaters and signal margins that are required for the coverage of specific tunnel with antennas. But in this thesis work for the AA-LRT tunnel at piassa, only considered are the propagation losses and extra attenuation due to curvature of the tunnel and get rid of other attenuations like;

- **Losses due to roughness→** this is because modern railway tunnels are smooth and for simplicity
- **Tilt loss→** this is due to its significance only in tunnels with semi-circular geometry (which is not my case)
- **Loss due to antenna coupling factor→** this is due to the need of field measurements which is not the scope of this thesis.

3.5. Summary

It is concluded that the model is accurate enough to predict losses in a tunnel and to determine the number of transmitters, power, antenna gain, and location to obtain good coverage for a specific signal level inside the tunnel. In the curved area it is necessary to add extra losses. Finally a complete propagation model for railway applications has been proposed. The model has combined the use of modal analysis in straight zones with the use of ray tracing to calculate extra attenuation in curves.

Chapter 4

ULTRA-WIDE BAND COMMUNICATION SYSTEMS OVERVIEW

4.1. Introduction

The recent rapid growth in technology and the successful commercial deployment of wireless communications are significantly affecting our daily lives. The transition from analog to digital cellular communications, the rise of third- and fourth-generation radio systems, and the replacement of wired connections with Wi-Fi and Bluetooth are enabling consumers to access a wide range of information from anywhere and at any time. As the consumer demand for higher capacity, faster service, and more secure wireless connections increases, new enhanced technologies have to find their place in the overcrowded and scarce radio frequency (RF) spectrum. This is because every radio technology allocates a specific part of the spectrum; for example, the signals for TVs, radios, cell phones, and so on are sent on different frequencies to avoid interference to each other. As a result, the constraints on the availability of the RF spectrum become more and more strict with the introduction of new radio services [14].

The need for speed, mobility and flexibility in electronic media products has increased the interest in wireless alternatives. Heinrich Hertz and Marconi developed the first transceiver in the late nineteenth century before the carrier wave was invented. Today it is called Ultra Wideband Radio (UWB) and sends information with pulses instead of the commonly used carrier wave. UWB has for many years been used in radar systems and in army communication but has not been allowed on the open market before 2002. The advantage with UWB is its potential to send high data rates (480 Mbps) over short distances [14].

Ultra-wideband (UWB) technology offers a promising solution to the RF spectrum drought by allowing new services to coexist with current radio systems with minimal or no interference. This coexistence brings the advantage of avoiding the expensive spectrum licensing fees that providers of all other radio services must pay.

UWB radio, operating with extremely large bandwidths, must coexist with many other interfering narrow-band signals (TV, GSM, UMTS, GPS, etc). In the same time, these narrow-band systems must not suffer intolerable interference from the UWB radios. Regulatory considerations over such a wide bandwidth limit the radiated power. The low transmit power levels together with the ultra-fine time resolution of the system can increase considerably the synchronization acquisition time and the complexity of the receiver. The Federal Communications Commission in USA (FCC) has defined an UWB device as any device with a –10 dB fractional bandwidth, greater than 20% or occupying at least 500 MHz of the spectrum **[7]**. Most narrowband systems occupy less than 10% of the center frequency bandwidth, and are transmitted at far greater power levels. For example, if a radio system were to use the entire UWB spectrum from 3.1- 10.6 GHz, and center about almost any frequency within that band, the bandwidth used would have to be greater than 100% of the center frequency in order to span the entire UWB frequency range. By contrast, the 802.11b radio system centers about 2.4 GHz with an operating bandwidth of 80MHz. This communication system occupies a bandwidth of only 1% of the center frequency [7].

The FCC also regulated the spectral shape and maximum power spectral density (-41.3dBm/MHz) of the UWB radiation in order to limit the interference with other communication systems. The power spectral density is the average power in the signal per unit bandwidth and hence provides important information on the distribution of power over the RF spectrum.

4.2. History and background

Ultra-wideband communications is fundamentally different from all other communication techniques because it employs extremely narrow RF pulses to communicate between transmitters and receivers. Utilizing short-duration pulses as the building blocks for communications directly generates a very wide bandwidth and offers several advantages, such as large throughput, covertness, robustness to jamming, and coexistence with current radio services.

Ultra-wideband communications is not a new technology; in fact, it was first employed by Guglielmo Marconi in 1901 to transmit Morse code sequences across the Atlantic Ocean using spark gap radio transmitters. However, the benefit of a large bandwidth and the capability of implementing multiuser systems provided by electromagnetic pulses were never considered at that time.

Approximately fifty years after Marconi, modern pulse-based transmission gained momentum in military applications in the form of impulse radars. From the 1960s to the 1990s, this technology was restricted to military and Department of Defense (DoD) applications under classified programs such as highly secure communications. However, the recent advancement in micro-processing and fast switching in semiconductor technology has made UWB ready for commercial applications. Therefore, it is more appropriate to consider UWB as a new name for a long-existing technology [14].

As interest in the commercialization of UWB has increased over the past several years, developers of UWB systems began pressuring the FCC to approve UWB for commercial use. In February 2002, the FCC approved the First Report and Order (R&O) for commercial use of UWB technology under strict power emission limits for various devices [14].

4.3. UWB concepts

Traditional narrowband communications systems modulate continuous waveform (CW) RF signals with a specific carrier frequency to transmit and receive information. A continuous waveform has a well-defined signal energy in a narrow frequency band that makes it very vulnerable to detection and interception. Figure below represents a narrowband signal in the time and frequency domains. UWB systems use carrierless, short-duration (picoseconds to nanoseconds) pulses with a very low duty cycle (less than 0.5 percent) for transmission and reception of the information.

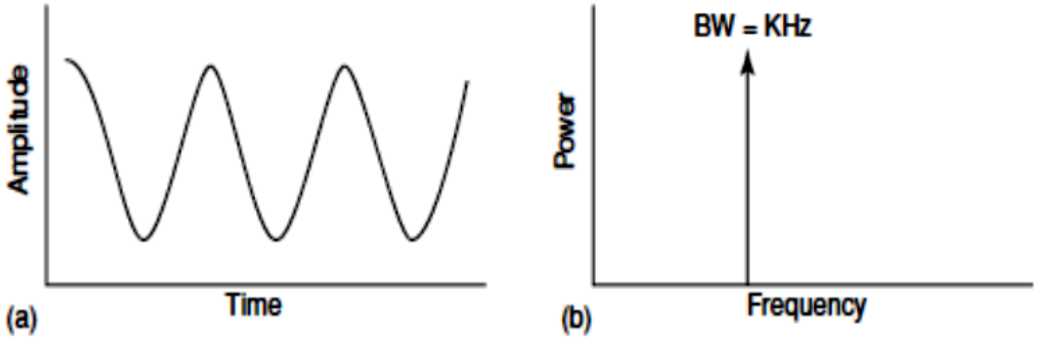


Figure 4.1 A narrowband signal in (a) the time domain and (b) the frequency domain

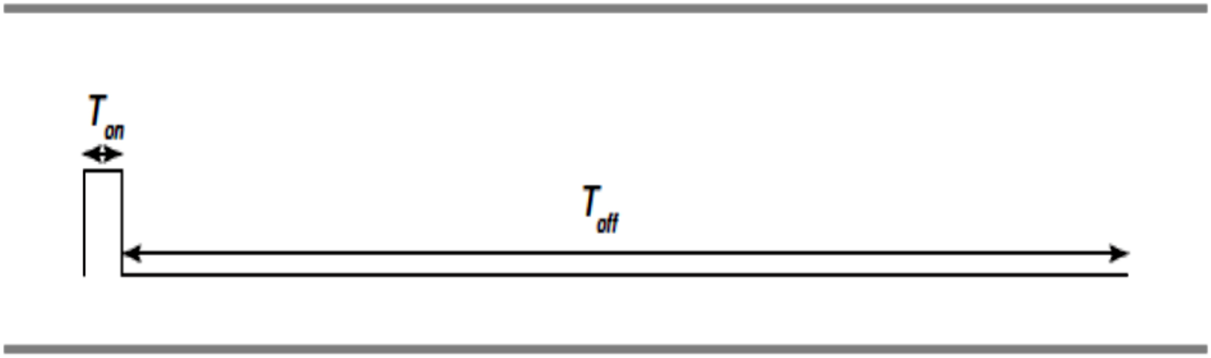


Figure 4.2 A low-duty-cycle pulse. T_{on} represents the time that the pulse exists and T_{off} represents the time that the pulse is absent

A simple definition for duty cycle is the ratio of the time that a pulse is present to the total transmission time.

$$Duty\ Cycle = \frac{T_{on}}{T_{off} + T_{on}}$$

Low duty cycle offers a very low average transmission power in UWB communications systems. The average transmission power of a UWB system is on the order of microwatts, which is a thousand times less than the transmission power of a cell phone! However, the peak or instantaneous power of individual UWB pulses can be relatively large, (The peak power of UWB pulses in some cases is reported to be about 1 watt for 1 Mbps at 1 MHz) but because they are transmitted for only a very short time ($T_{on} < 1$ nanosecond), the average power becomes considerably lower. Consequently, UWB devices require low transmit power due to this control over the duty cycle, which directly translates to longer battery life for handheld equipment. Since frequency is inversely related to time, the short-duration UWB pulses spread their energy across a wide range of frequencies from near DC to several Gigahertzes (GHz) with very low power spectral density (PSD) [14]. (Power spectral density is the signals' power in the frequency domain)

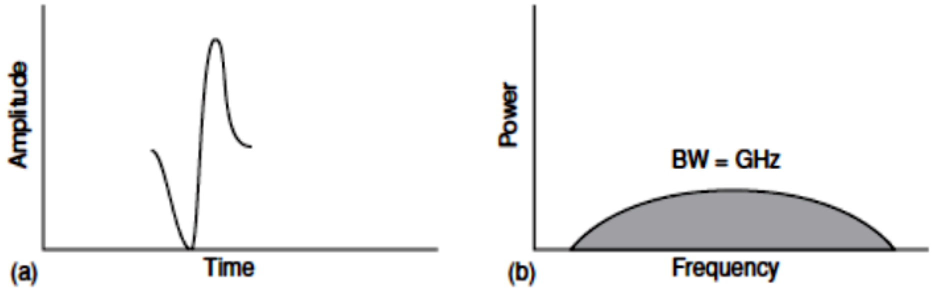


Figure 4.3 A UWB pulse in (a) the time domain and (b) the frequency domain

4.4. UWB signals

As defined by the FCC’s First Report and Order, UWB signals must have bandwidths of greater than 500 MHz or a fractional bandwidth larger than 20 percent at all times of transmission. Fractional bandwidth is a factor used to classify signals as narrowband, wideband, or ultra-wideband and is defined by the ratio of bandwidth at –10 dB points (The –10 dB point represents the spectral power of a signal at 10 dB lower than its peak power) to center frequency. Equation below shows this relationship.

$$B_f = \frac{BW}{f_c} \times 100\% = \frac{(f_h - f_l)}{(f_h + f_l)/2} \times 100\% = \frac{2(f_h - f_l\ )}{f_h + f_l} \times 100\%$$

Where f_h and f_1 are the highest and lowest cutoff frequencies (at the –10 dB point) of a UWB pulse spectrum, respectively. A UWB signal can be any one of a variety of wideband signals, such as Gaussian, chirp, wavelet, or Hermite-based short-duration pulses. Figure below represents a Gaussian monocycle as an example of a UWB pulse in the time and frequency domains. The Gaussian monocycle is the first derivative of a Gaussian pulse and is given by

$$P(t) = \frac{t}{\tau} e^{-(\frac{t}{\tau})^2}$$

Where **t** represents time and **τ** is a time decay constant that determines the temporal width of the pulse. As shown in Figure below, a 500-picosecond pulse generates a large bandwidth in the frequency domain with a center frequency of 2 GHz. The lowest and highest cutoff frequencies at –10 dB are approximately 1.2 GHz and 2.8 GHz, respectively, which lead to a fractional bandwidth of 80 percent; this is much larger than the minimum B_f required by the FCC:

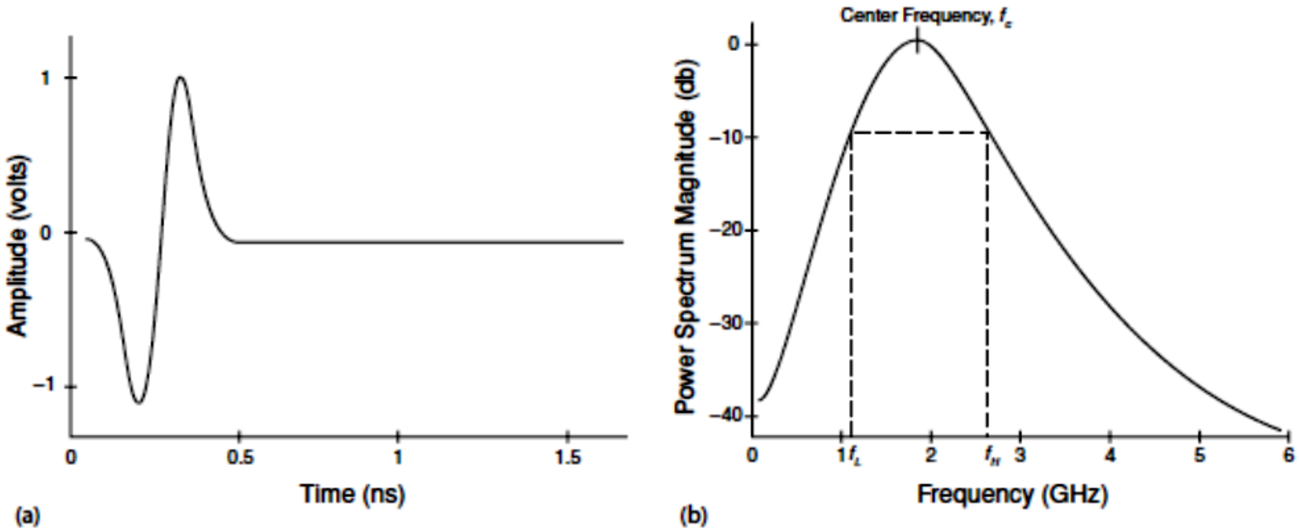


Figure 4.4 Generated UWB Signal

$$B_f = 2 * \frac{2.8 - 1.2}{2.8 + 1.2} * 100\% = 80\%$$

Here is the classification of signals based on their fractional bandwidth:

Narrowband $B_f < 1\%$

Wideband $1\% < B_f < 20\%$

Ultra-Wideband $B_f > 20\%$

For example, 802.11 and Bluetooth have fractional bandwidths of 0.8 percent and 0.04 percent, respectively[14].

4.5. Short-pulse generation

In general, UWB radio systems transmit and receive single band or multi-band pulses. Single-Band (SB) based, employing one single transmission frequency band, and Multi-Band (MB) based, employing two or more frequency bands, each with at least 500 MHz bandwidth. In the

SB solution, the UWB signal is generated using very short, low duty-cycle, baseband electrical pulses with appropriate shape and duration. Due to the carrier-less characteristics, no sinusoidal carrier to raise the signal to a certain frequency band, these UWB systems are also referred to as carrier-free or impulse radio (IR-UWB) communication systems [7]. Such systems are capable of providing low system complexity and low cost because of their direct transmission and reception of pulsed signals and the least RF devices in their front-ends as against conventional narrowband radio systems [7].

The MB-UWB system is implemented carrier less (different pulse shapes/lengths are used according to the frequency band) or carrier based (multi-carrier like) known as UWB orthogonal frequency division multiplexing(UWB-OFDM). In UWB-OFDM bandwidth is split into many sub-bands applying communication techniques well-known from narrowband systems. The requirements for UWB antennas can vary for different schemes. In the multiband scheme, the consistent or flat gain response of the UWB antennas is more important than a constant group delay or a linear phase response, which is conversely more important in the single band scheme. Therefore, the performance of UWB antennas can be assessed in terms of the system transfer function and group delay together with conventional frequency-domain parameters such as return loss, gain, radiation patterns, and polarization matching path loss as well as the time-domain parameters such as pulse waveforms, and fidelity [7].

In the IR-UWB, typically the radiated pulse signals are generated without the use of local oscillators or mixers, thus potentially a simpler and cheaper construction of the transmitter (Tx) and receiver (Rx) is possible, as compared to the conventional narrow-band systems. The characteristics of the pulse used (shape, duration), determine the bandwidth and spectral shape of the UWB signals. The most common pulse shapes used in IR-UWB are: Gaussian monocycle (and its derivatives) and Hermitan pulses.

The impulse radio technology has been widely used in radar applications due to its spatial resolution, detectable material penetration, easy target detection and feature extraction and low probability of intercept signals. Military and government multi-user networking and high precision localization applications rely on the UWB communication systems [7].The basic properties of the impulse radio systems make the UWB technology ideal candidate also for commercial, short range, low power, and low-cost indoor communication systems.

4.6. Advantages of UWB radio

The nature of the short-duration pulses used in UWB technology offers several advantages over narrowband communications systems. Here are some of the key benefits that UWB brings to wireless communications.

4.6.1. Ability to share the frequency spectrum

The FCC's power requirement of –41.3dBm/MHz,(The abbreviation *dBm* stands for decibels per milliwatt. Hence, –41.3dBm/MHz is equal to 75nW/MHz.) equal to 75Nano watts/MHz for UWB systems, puts them in the category of unintentional radiators, such as TVs and computer monitors. Such power restriction allows UWB systems to reside below the noise floor of a typical narrowband receiver and enables UWB signals to coexist with current radio services with minimal or no interference [7]. However, this all depends on the type of modulation used for data transfer in a UWB system. Some modulation schemes generate undesirable discrete spectral lines in their PSD, which can both increase the chance of interference to other systems and increase the vulnerability of the UWB system to interference from other radio services. Figure below illustrates the general idea of UWB's coexistence with narrowband and wideband technologies.

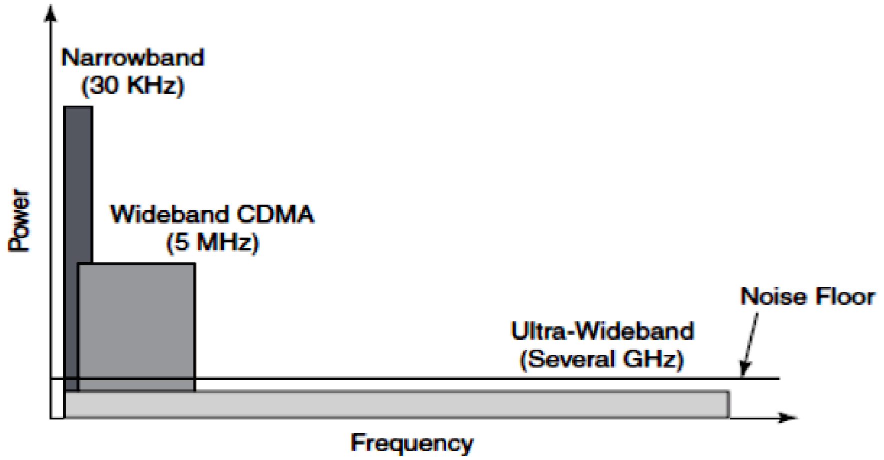


Figure 4.5 Coexistence of UWB signals with narrowband and wideband signals in the RF spectrum

4.6.2. Large channel capacity

One of the major advantages of the large bandwidth for UWB pulses is improved channel capacity. *Channel capacity,* or data rate, is defined as the maximum amount of data that can be transmitted per second over a communications channel. The large channel capacity of UWB communications systems is evident from Hartley-Shannon's capacity formula:

$$C = Blog\,(\mathbf{1} + SNR)$$

Where *C* represents the maximum channel capacity, *B* is the bandwidth, and *SNR* is the signal-to-noise power ratio. As shown in Equation above, channel capacity *C* linearly increases with bandwidth *B*. Therefore, having several Gigahertz of bandwidth available for UWB signals, a data rate of Gigabits per second (Gbps) can be expected. However, due to the FCC's current power limitation on UWB transmissions; such a high data rate is available only for short ranges. This makes UWB systems perfect candidates for short-range, high-data-rate wireless applications. The trade-off between the range and the data rate makes UWB technology ideal for a wide array of applications in military, civil, and commercial sectors.

4.6.3. Ability to work with low signal-to-noise ratios

The Hartley-Shannon formula for maximum capacity also indicates that the channel capacity is only logarithmically dependent on signal-to-noise ratio (SNR). Therefore, UWB communications systems are capable of working in harsh communication channels with low SNRs and still offer a large channel capacity as a result of their large bandwidth.

4.6.4. Low probability of intercept and detection

Because of their low average transmission power, UWB communications systems have an inherent immunity to detection and intercept. With such low transmission power, the eavesdropper has to be very close to the transmitter (about 1 meter) to be able to detect the transmitted information [7]. In addition, UWB pulses are time modulated with codes unique to each transmitter/receiver pair. The time modulation of extremely narrow pulses adds more security to UWB transmission, because detecting picoseconds pulses without knowing when they will arrive is next to impossible. Therefore, UWB systems hold significant promise of achieving highly secure, low probability of intercept and detection (LPI/D) communications that is a critical need for military operations.

4.6.5. Resistance to jamming

Unlike the well-defined narrowband frequency spectrum, the UWB spectrum covers a vast range of frequencies from near DC to several Gigahertzes and offers high processing gain for UWB signals [7]. Processing gain (PG) is a measure of a radio system's resistance to jamming and is defined as the ratio of the RF bandwidth to the information bandwidth of a signal:

$$PG = \frac{RF\ Bandwidth}{Information\ Bandwidth}$$

The frequency diversity caused by high processing gain makes UWB signals relatively resistant to intentional and unintentional jamming, because no jammer can jam every frequency in the UWB spectrum at once. Therefore, if some of the frequencies are jammed, there is still a large range of frequencies that remains untouched.

4.6.6. High performance in multipath channels

The phenomenon known as multipath is unavoidable in wireless communications channels. It is caused by multiple reflections of the transmitted signal from various surfaces such as buildings, trees, and people. The straight line between a transmitter and a receiver is the line of sight(LOS); the reflected signals from surfaces are non-line of sight (NLOS). Figure below represents the multipath phenomenon in narrowband and UWB signals.

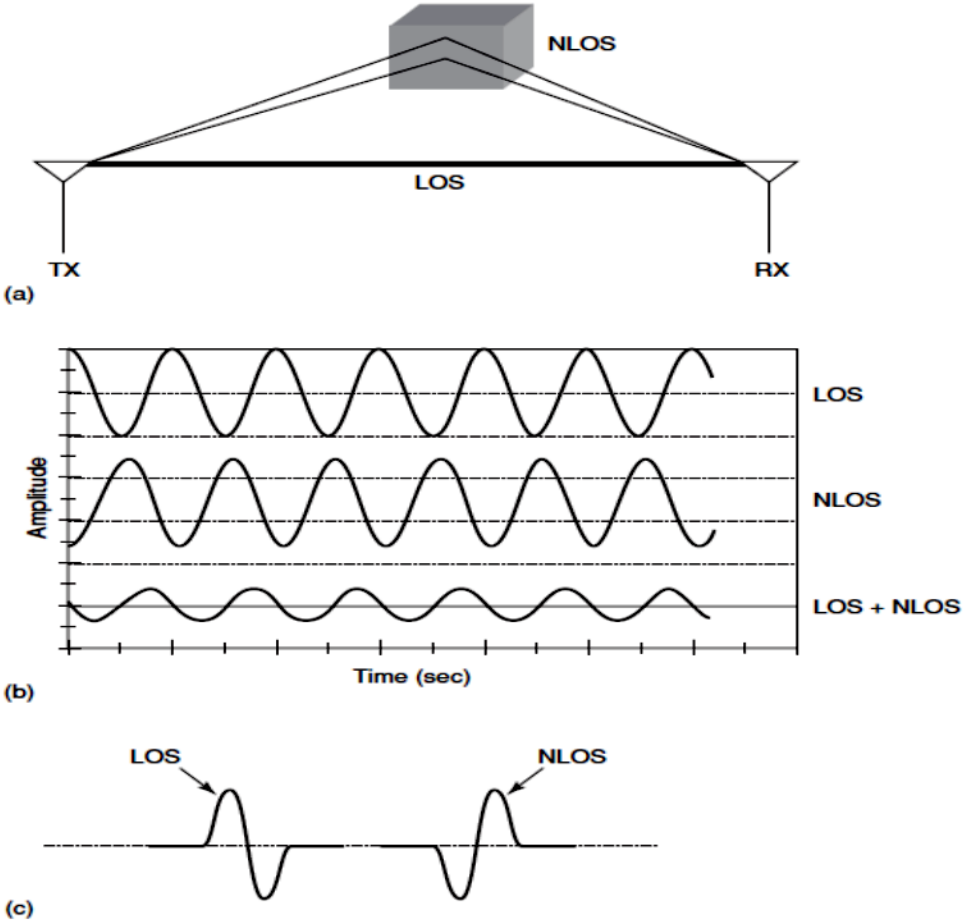


Figure 4.6 (a) The multipath phenomenon in wireless links (b) Multipath effects

As shown in Figure above, the effect of multipath is rather severe for narrow band signals; it can cause signal degradation up to **–40 dB** due to the out-of-phase addition of LOS and NLOS continuous waveforms [7]. On the other hand, the very short duration of UWB pulses makes them less sensitive to the multipath effect. Because the transmission duration of a UWB pulse is shorter than a nanosecond in most cases, the reflected pulse has an extremely short window of opportunity to collide with the LOS pulse and cause signal degradation.

4.6.7. Superior penetration properties

Unlike narrowband technology, UWB systems can penetrate effectively through different materials. The low frequencies included in the broad range of the UWB frequency spectrum have long wavelengths, which allows UWB signals to penetrate a variety of materials, including walls. This property makes UWB technology viable for through-the-wall communications and ground-penetrating radars. However, the material penetration capability of UWB signals is useful only when they are allowed to occupy the low-frequency portion of the radio spectrum.

4.6.8. Simple transceiver architecture

UWB transmission is carrierless, meaning that data is not modulated on a continuous waveform with a specific carrier frequency, as in narrowband and wideband technologies. Carrierless transmission requires fewer RF components than carrier based transmission. For this reason UWB transceiver architecture is significantly simpler and thus cheaper to build. Figure below compares the block diagrams of typical narrowband and UWB transceivers. As shown in Figure below, the UWB transceiver architecture is considerably less complicated than that of the narrowband transceiver. The transmission of low-powered pulses eliminates the need for a power amplifier (PA) in UWB transmitters. Also, because UWB transmission is carrierless, there is no need for mixers and local oscillators to translate the carrier frequency to the required frequency band; consequently there is no need for a carrier recovery stage at the receiver end.

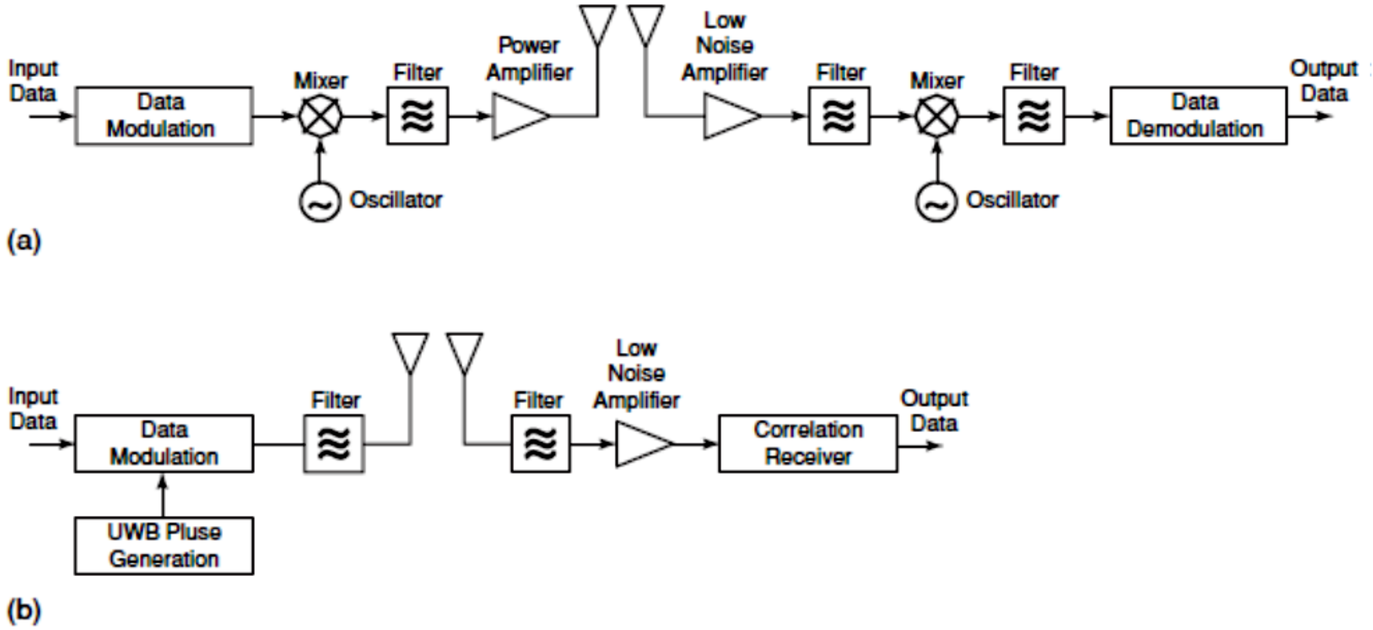


Figure 4.7 (a) A typical narrowband transceiver architecture. (b) An example of a UWB Transceiver architecture

In general, the analog front end of a UWB transceiver is noticeably less complicated than that of a narrowband transceiver. This simplicity makes an all CMOS (short for complementary metal-oxide semiconductors) implementation of UWB transceivers possible, which translates to smaller form factors and lower production costs.

Advantage	**Benefit**
Coexistence with current narrowband and wideband radio services	Avoids expensive licensing fees.
Large channel capacity	Offers high performance in noisy environments.
Low transmit power	Provides high degree of security with low probability of detection and intercept.
Resistance to jamming	Reliable in hostile (antagonistic) environments

High performance in multipath channels	Delivers higher signal strengths in adverse (harmful; unfavorable) conditions
Ability to work with low SNRs	Offers high performance in noisy environments.
Simple transceiver architecture	Enables ultra-low power, smaller form factor, and better mean time between failures, all at a reduced cost.

Table 4.1 Advantages and benefits of UWB communications

Here are some challenges and problems need to be focused and solved while implementing the UWB radio communication system:

Challenge	**Problem**
Pulse-shape distortion	Low performance using classical matched filter receivers.
High-frequency synchronization	Very fast ADCs required.
Low transmission power	Information can travel only short distances.

Table 4.2 some challenges and problems associated with UWB systems

4.7. UWB pulse shapes

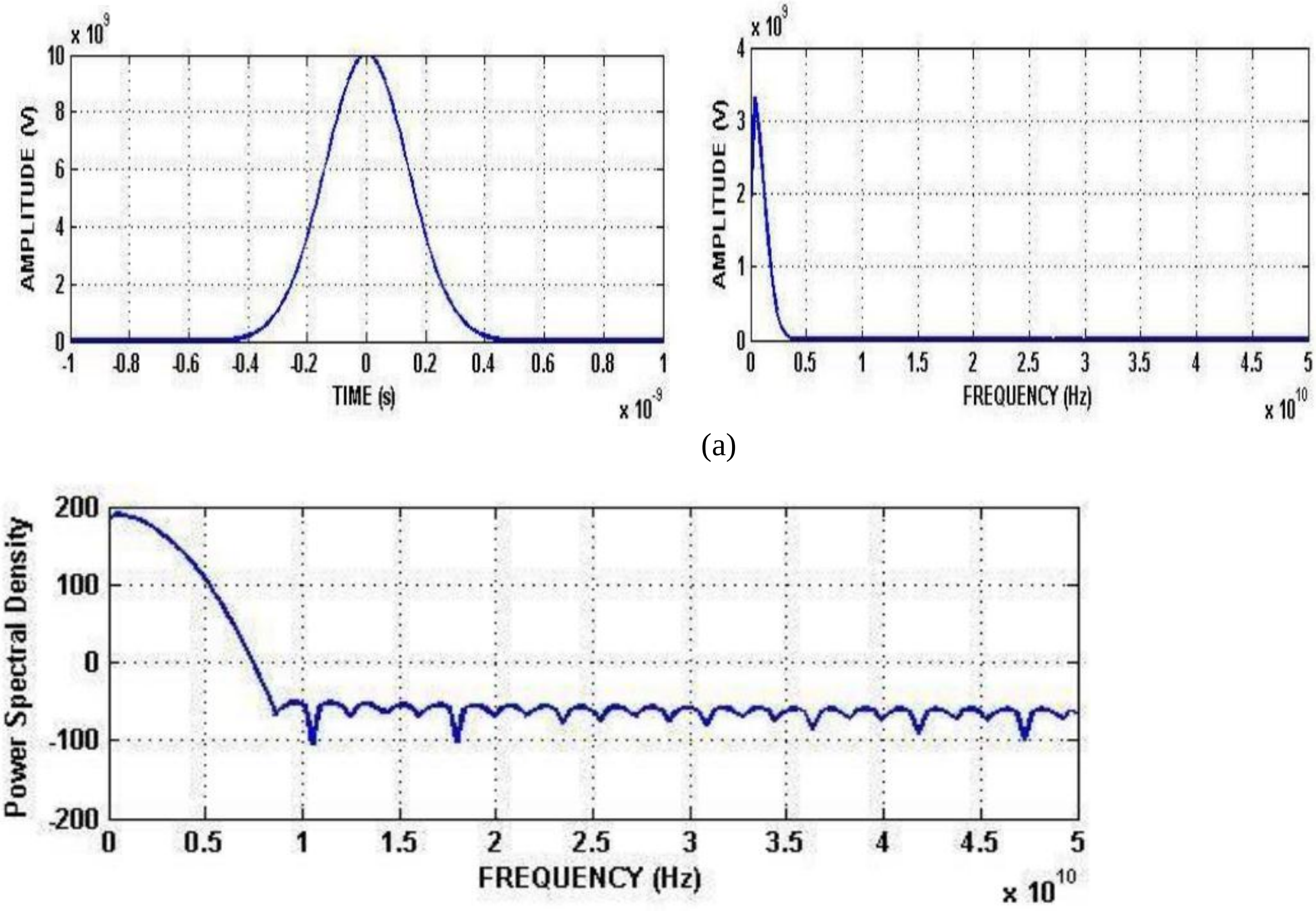
UWB systems employ non sinusoidal wave shapes that should have certain properties when transmitted from antenna. Emission in UWB communication systems are constrained by the FCC regulation, which states that ‘intentional radiators that produce class B emission (damped wave) are prohibited. Several non-damped waveforms are available for UWB systems, they are usually referred as Gaussian pulse, Gaussian monocycle (Gaussian pulse of first derivative), Gaussian doublet (Gaussian pulse of second derivative) and Orthogonal polynomial based pulses like Modified Gegenbauer Functions (MGF) [3]. Such waveforms spread the energy over a large bandwidth as they have sharp rise and fall. In addition, the power spectral density is so low for any given frequency that it provides the possibility of low probability of detection or intercepts communications. The short pulses also offer immunity to multipath fading and a much lower fading margin, which gives multipath resolution.

4.7.1. Gaussian Pulse

The zero mean Gaussian pulse is represented by the following equation.

$$x(t) = \frac{1}{\sqrt{2\pi\sigma^2}} exp(\frac{-t^2}{2\sigma^2})$$

In equation, **σ** is standard deviation which also works as time decay constant that determines the impulse duration, and **t** is the time.



(a)

(b)

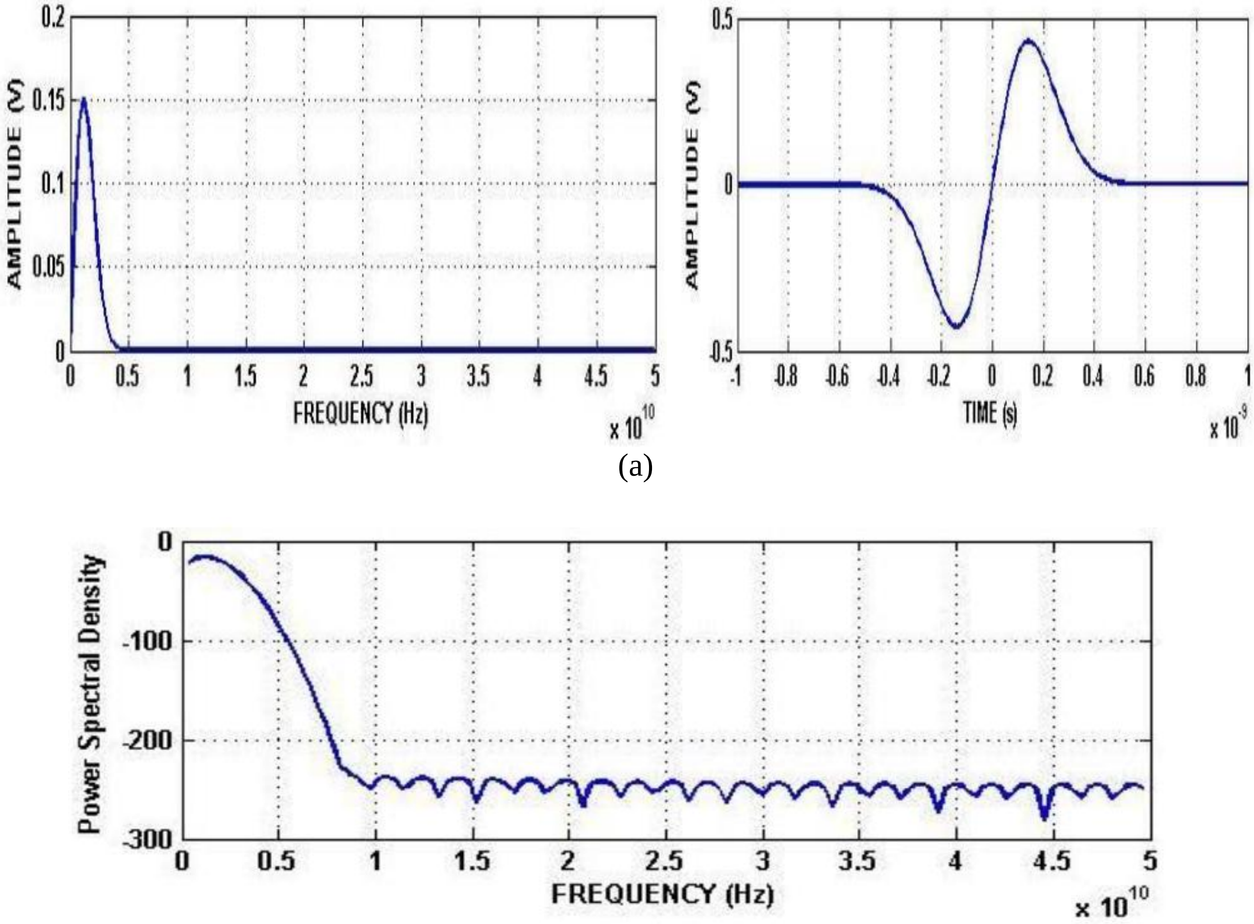
Figure 4.8 (a) Gaussian pulse in time, frequency domain and (b) power spectral density

4.7.2. Gaussian Mono-cycle

The Gaussian monocycle pulse is described as:

$$x'(t) = -\frac{t}{\sqrt{2\pi\sigma^3}}\exp(-\frac{t^2}{2\sigma^2})$$

This waveform is mathematically similar to the first derivative of the Gaussian function.



(a)

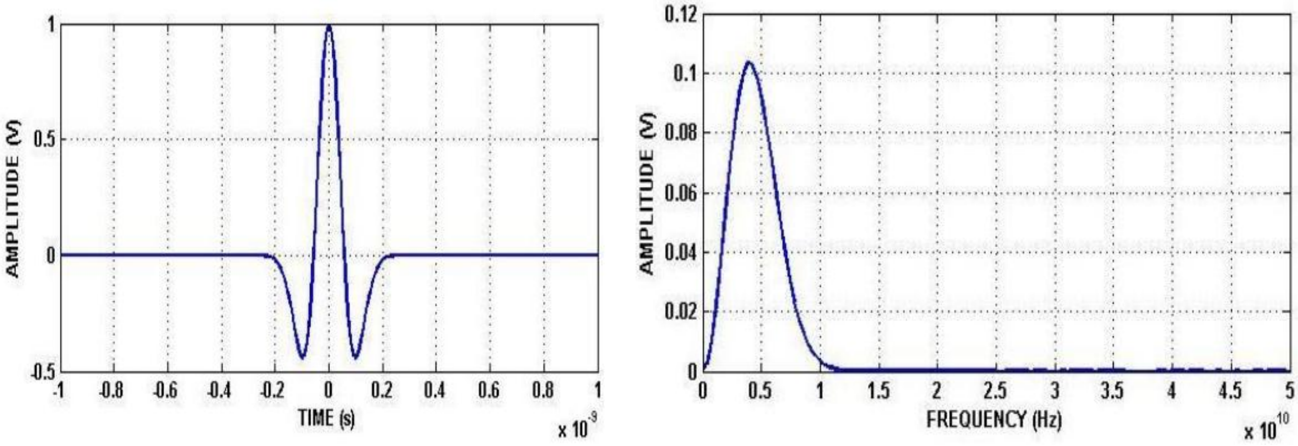
(b)

Figure 4.9 (a) Gaussian Mono-cycle in time, frequency domain and (b) power spectral density

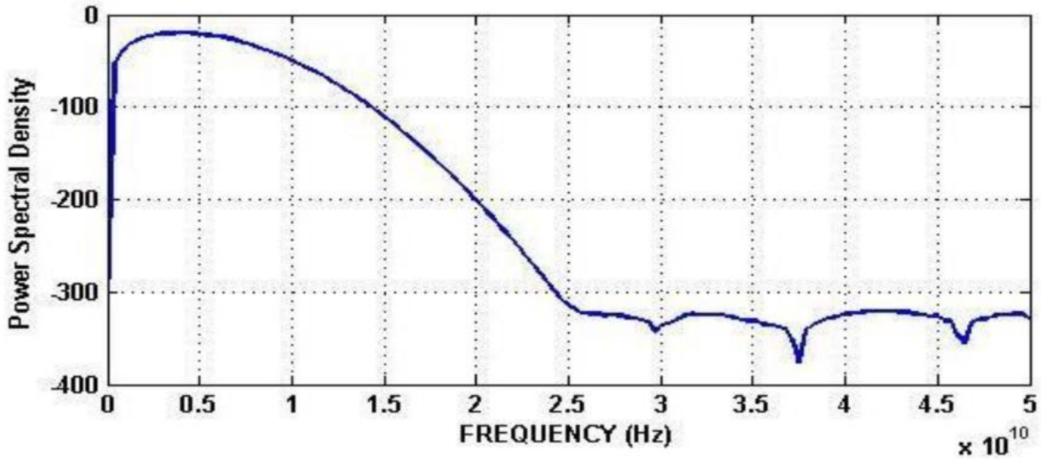
4.7.3. Gaussian Doublet

One of the simplest UWB waveforms also to be considered is the Gaussian mono pulse or Gaussian doublet. This represents the second derivative of the Gaussian pulse. Its waveform is given by the equation:

$$x''(t) = -\frac{1-\frac{t^2}{\sigma^2}}{\sqrt{2\pi}\sigma^3}\exp(\frac{-t^2}{2\alpha^2})$$



(a)



(b)

Figure 4.10 (a) Gaussian doublets in time, frequency domain and (b) power spectral density

4.7.4. Truncated sinus

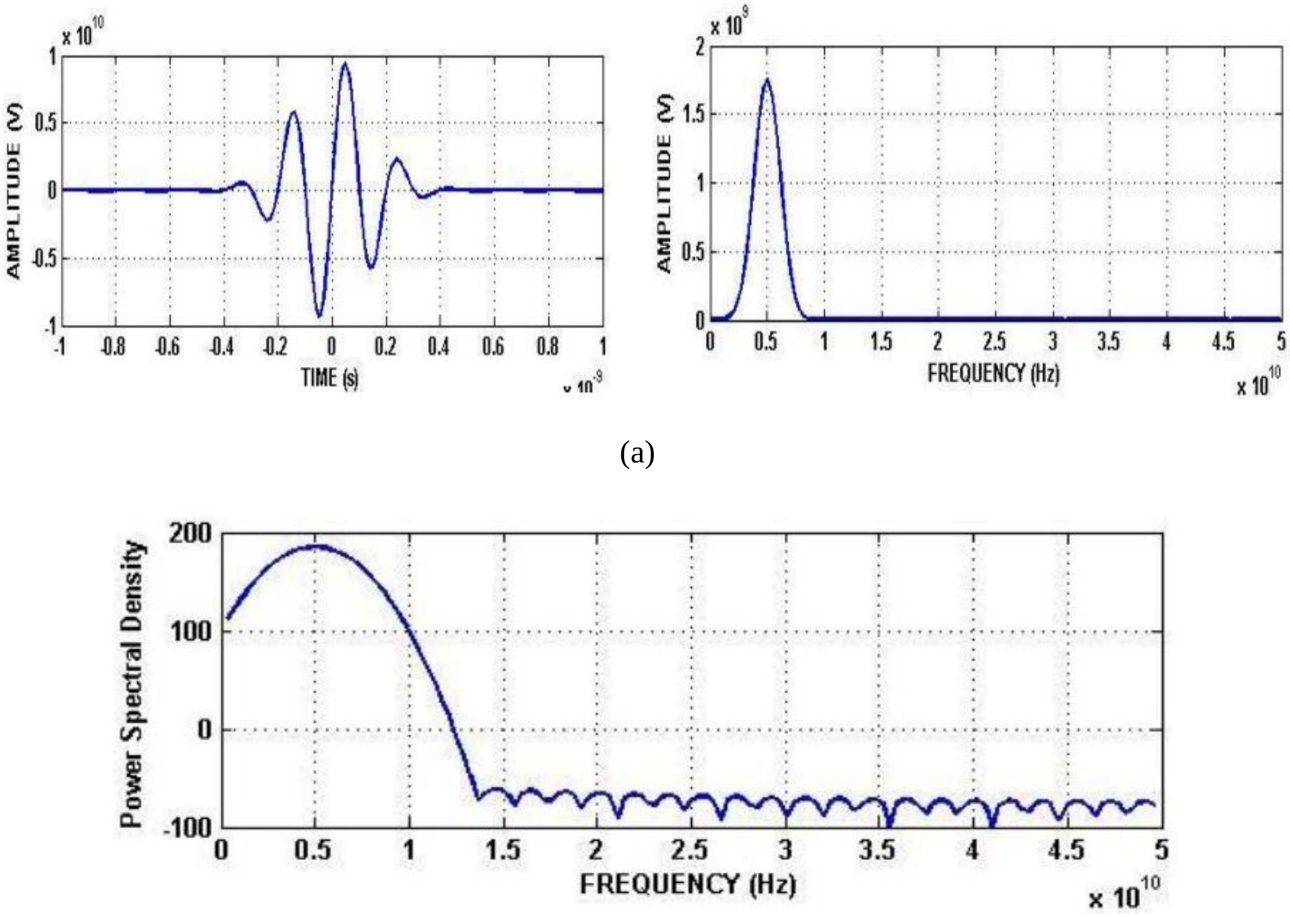
The truncated sinusoid is also often used. It proves to be convenient for simulation and analyses in UWB systems. Its expression is given by following equation

$$x(t) = \begin{Bmatrix} f(t).\sin(\omega_r t), 0 \le t < NT \\ 0, Else \end{Bmatrix}$$

$\omega_r = \frac{2\pi}{T}$ Pulsation

N: The number of cycles per period T.

f(t): truncation function (rectangle, triangle, Gaussian...)



(a)

(b)

Figure 4.11 (a) Truncated sinusoidal pulse in time, frequency domain and (b) power spectral density

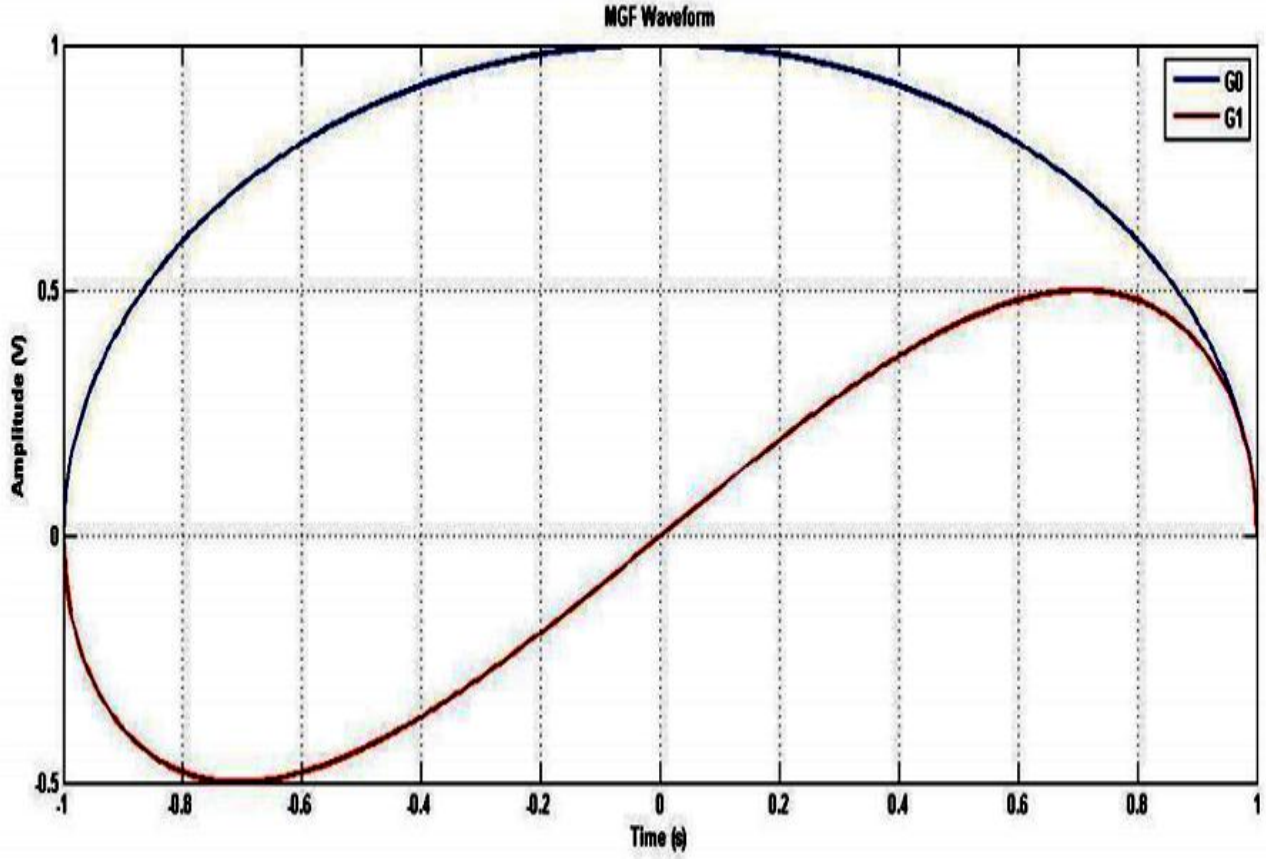
4.7.5. Orthogonal polynomial based pulse

Modified Gegenbauer Functions (MGF) based impulse also found very good application in UWB system. They are well suited due to theirs orthogonally and multiplexing capabilities[3]. The Gegenbauer polynomials use the weight function$w\,(x) = (1 - x^2)^{(\beta - \frac{1}{2})}$ where, $\beta > -\frac{1}{2}$ is a wave shape parameter. MGF polynomials are orthogonal in the interval [-1, 1]. Where n is the degree of polynomial. Following equations shows the first two orders of MGF polynomials:

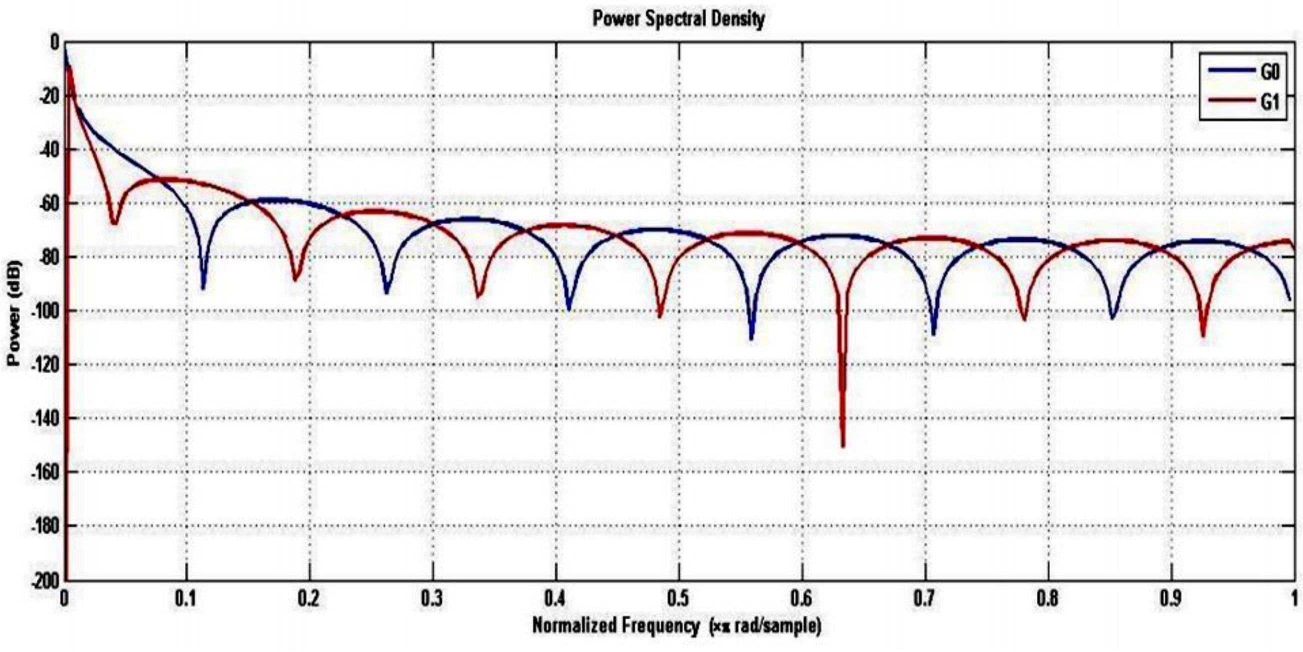
$G_0 = 1,$

$G_1 = 2\beta x,$

$G_2 = (-\beta + 2\beta(1 + \beta)x^2$



(a)



(b)

Figure 4.12 MGF function (a) in time domain and (b) power spectral density

4.8. Current FCC regulations

The FCC spectral mask (that is, the operating restrictions for UWB in the United States) specifies 7.5 GHz of usable spectrum bandwidth between 3.1 GHz and 10.6 GHz for communications devices. The FCC also protects existing users operating within this spectrum by limiting the UWB signal's transmit power. The UWB devices' power spectral density levels are limited to –41.3dBm/MHz. The primary difference between indoor and outdoor operation is the higher degree of attenuation required for the out-of- band region for outdoor operations. This further protects GPS receivers, centered at 1.6 GHz.

4.9. FCC emission limits

In order to protect existing radio services from UWB interference, the FCC has assigned conservative emission masks between 3.1 GHz and 10.6 GHz for commercial UWB devices. The maximum allowed power spectral density for these devices that is, –41.3dBm/MHz, or 75nW/MHz places them at the same level as unintentional radiators (FCC Part 15 class) such as televisions and computer monitors. Based on the FCC regulations, UWB devices are classified into three major categories: communications, imaging, and vehicular radar.

4.9.1. Communications devices

For communications devices, the FCC has assigned different emission limits for indoor and outdoor UWB devices. The spectral mask for outdoor devices is 10 dB lower than that for indoor devices, between 1.61 GHz and 3.1 GHz.

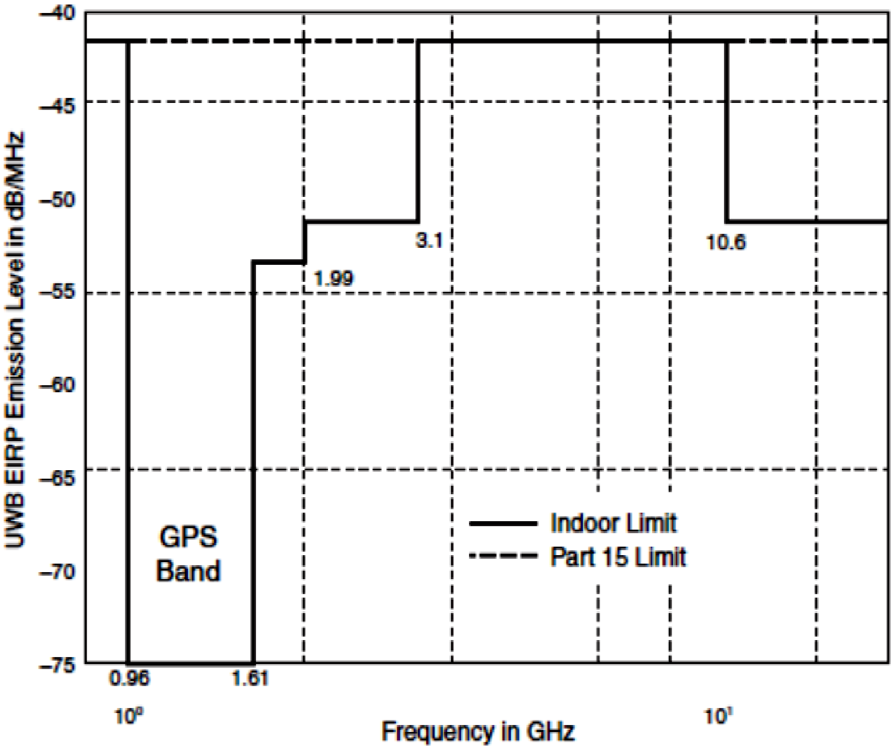


Figure 4.13 UWB emission limits for indoor communications systems. From E. Thomas, “Walk Don’t Run: The First Step in Authorizing Ultra-Wideband Technology,” IEEE Conference on Ultra Wideband Systems and Technologies (UWBST), May 2002. Copyright © 2002 IEEE.

	Application		**Operation Band (GHz)**					
			0.96 to 1.61	**1.61 to 1.99**	**1.99 to 3.1**	**3.1 to 10.6**	**10.6 to 22.0**	**22.0 to 29.0**
		BW(GHz)	0.45	0.38	1.11	7.50	11.40	7.00
ERIP (dBm)	Communications	Indoor	–75.3	–53.3	–51.3	–41.3	–51.3	–51.3
		Outdoor	–75.3	–63.3	–61.3	–41.3	–61.3	–61.3
	Imaging		–53.3	–51.3	–41.3	–41.3	–41.3	–51.3
	Vehicular Radar		–75.3	–63.3	–63.3	–63.3	–41.3	–41.3

Table 4.3 Emission limits for various UWB applications in each operational band

	IEEE Standard						
	WLAN			**Bluetooth**	**WPAN**	**UWB**	**ZigBee**
	802.11a	802.11b	802.11g	802.15.1	802.15.3	802.15.3a	802.15.4
Operational Frequency	5 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	3.1–10.6 GHz	2.4 GHz
Maximum Data Rate	54 Mbps	11 Mbps	54 Mbps	1 Mbps	55 Mbps	> 100 Mbps	250 Kbps
Maximum Range	100 meters	100 meters	100 meters	10 meters	10 meters	>10 meters	50 meters

Table 4.4 UWB capabilities compared to other IEEE standards

	Applications	
	Military and Government	**Commercial**
Data Communications	Secure LPI/D communications Covert wireless sensor networks (battlefield operations)	Local and personal area networks Wireless streaming video distribution (home networking) Wireless sensor networks (health and habitat monitoring, home automation)
Radar	Through-wall imaging (for law enforcement, firefighters) Ground-penetrating radar (for rescue operations) Surveillance and monitoring	Medical imaging (remote heart monitoring) Ground-penetrating radar (detection of electrical wiring, studs, etc. on construction sites) Automotive industry (collision avoidance, roadside assistance) Home security (proximity detectors)
Localization	Personnel identification Lost children Prisoner tracking	Inventory tracking Tagging and identification Asset management

Table 4.5 Some UWB applications in military and commercial sectors

4.10. Summary

With the recent advances in semiconductor device technology and the FCC’s approval of the unlicensed use of ultra-wideband systems, UWB development has moved from research labs and classified military. In this chapter, the history, background, and basic concepts of UWB communications are reviewed. The major advantages and challenges of this emerging technology are identified and the fundamental differences between narrowband, wideband, and ultra-wideband communications are reviewed.

Chapter 5

ULTRA-WIDE BAND COMMUNICATION SYSTEM FOR RAILWAY TUNNEL

5.1. Introduction

The wireless communications channel constitutes the basic physical link between the transmitter and the receiver antennas. Its modeling has been and continues to be a tantalizing issue, while being one of the most fundamental components based on which transmitters and receivers are designed and optimized. The ultimate performance limits of any communication system are determined by the channel it operates in [41]. Realistic channel models are thus has importance for system design and testing. In addition to exponential power path-loss, wireless channels suffer from stochastic short term fading (STF) due to multipath, and stochastic long term fading (LTF) due to shadowing depending on the geographical area. STF corresponds to severe signal envelope fluctuations, and occurs in densely built-up areas filled with lots of objects like buildings, vehicles, etc. On the other hand, LTF corresponds to less severe mean signal envelope fluctuations, and occurs in sparsely populated or suburban areas. In general, LTF and STF are considered as superimposed and may be treated separately [18].

UWB differ significantly from other wireless communication standards. UWB systems, here after called UWB, send series of pulses instead of using a carrier wave. The pulse can be seen as an intense burst of RF energy where each pulse carries one symbol of information. In contrast to a carrier wave, which has narrow bandwidth, the pulses have large bandwidth, giving the system potential for high data rates. Another advantage is that UWB can operate simultaneously with other RF products in the same frequency band. This gives UWB several areas of operation, e.g. in imaging systems, vehicular radar systems and communication and measurement systems [15]. A drawback when operating in the same frequency bands as other systems is that the pulses must be adapted not to disturb these systems.

5.2. Theory and Techniques

As mentioned before, UWB send information through pulses. The pulses are sent one by one, after each other with a given pulse repetition frequency (PRF). The pulses have large bandwidth, which means that the energy of a pulse is spread over a wide frequency band whereas a carrier wave system concentrates the energy on a specific frequency. Comparing these two alternatives, it can be seen that a pulse based system can have a lower average output power per MHz than a carrier wave based system and hence does not disturb the carrier wave under simultaneous operation. The pulses can be created in different ways and have different characteristics. The Gaussian pulse, which has a relative pulse width and the Hermite based pulses, which are based on polynomials are two alternatives for UWB pulses. The first order Hermite based pulse and the Gaussian monocycle are the same, increasing the order of the Hermite polynomial and the number of cycles in the Gaussian, the pulses begins to differ. While maintaining the same pulse width for both pulses, the amplitude is modulated differently and the Hermite does not sustain a consistent center frequency. Due to the mentioned differences of the pulses, the Gaussian pulse is more attractive for UWB use. Notice that the center frequency sets the position of the pulse in the frequency domain and the pulse width sets the bandwidth. A small pulse width sets a large bandwidth [15]. There are two different techniques used when optimizing a system for a given bandwidth, called “single band” and “multiple bands”. The single band technique uses one pulse with very large bandwidth while a set of pulses with different center frequencies is used in the multiple bands technique.

5.3. UWB radio communication and railway

Millions of people all over world depend on it for their daily needs, because of this railway transportation requires very safe and reliable mode of control and signalling systems. As discussed earlier that in past, wired technology was used for smooth operation of trains. Some of the protection issues are discussed below:

- Train traverse on fixed guided track, so sudden change in route is not possible, so in case to avoid obstacles it need to awareness well before in time. It could be possible by implementing well developed obstacle detection system [4].

- Operation of multiple trains on the same rails in opposite direction may cause collisions. So a traffic system which maintains the rules of right occupancy on the track is needed.
- Interruption in communication between train drivers and controllers may cause the loss of control over the train. So a fast and reliable system for data transmission is needed.
- Localization of train at any time any point on the track so that passengers can get timely updated information about the train running status.

In past, various detection and communication systems were used to detect the obstacles on the track and to avoid the collision. Examples are electrified slide fences, use of light beams and photo-detectors, seismometers [4] etc., but these systems were not much accurate as they depend on some foresight and also their installation cost was very high, that they cannot employed throughout the railway track.

Now those wired signalling systems are replaced by the wireless communication and signalling systems. This enables to enhance the safety and efficiency of railway management. Ultra wide band radio based wireless communication emerges as a rapid growing technology which has tremendous capability of simultaneous train to wayside communication, train location and obstacle detection and data transmission with high data rate [5].

The UWB based signalling system is very effective for urban transport systems which has a line operate inside underground tunnel. Underground transportation systems are maintained by control and command centers [28]. Role of control and command centers are to collect the information about the vehicle from their source to destination. Some very important information to collect is location of train, speed, acceleration, direction and condition of vehicles. The most popular and practically implemented control and command system is communication based train control (CBTC). For efficient and smooth functioning of railway system, effective and highly available train to track communication system is must. Day by day increasing traffic and amount of data transmission creates problem to maintain an efficient train to wayside communication. Performance of existing communication systems are limited by the harsh environmental and construction problem related with tunnel and urban transportation. According to propagation phenomena this environment conditions can be characterized as multipath fading effect, frequency selectivity, distance and frequency dependent path-loss. Conventional narrow-band communication systems are severely affected by these propagation characteristics, so it is replaced by the large-bandwidth communication system [5].These problems associated with the propagation of waves inside railway tunnels has been studied and explained in detail in this thesis, by using UWB radio based wireless communication system.

5.4. Ultra wideband channel characteristics

Channel is a medium through which message convey to one or many receivers from the transmitter. It could be wired or wireless, having a fixed capacity of data transmission. In any communication system channel is a very important part as channel characteristics decides the propagation characteristics and quality of transmission and reception. Before studying the design consideration of a UWB communication system, it is important to understand about the ultra-wideband propagation channel. So first it is good to be aware of the fundamental properties of UWB channels, and how it is different from those conventional narrow band channels [10]. UWB system has relatively very large bandwidth hence the propagation process, path loss and shadowing effect become frequency dependent. Fundamental properties of UWB propagation are:

Multipath Propagation: Multipath waves are the multiple versions of transmitted signal that arrives at the receiving antenna. A single transmitted signal split into multiple components because of reflection, diffraction and scattering from various environmental objects like mountains, houses, trees, walls etc. these multipath component could be different in phase and amplitude from the actual one. The random change in phase and amplitude of the different multipath components cause fluctuations in signal strength, which produces small scale fading effect and/or signal distortion. Since the multipath components traverse through different path so depending upon the length of path, time delay of arrival increases which may cause inter symbol interference. The signal at receiver side can be represented as the sum of scaled and delayed replicas of the transmitted signal and the channel impulse response can be represented mathematically as:

$$h(t) = \sum_{i=1}^{N} a_i \delta(t - \tau_i)$$

Where a_i is the gain and τ_i is the time delay of multipath components. The above equation for channel impulse response based on some limitations, as objects causes to produce multipath components may be time variant but equation is not including those factors. Also it's not including the frequency dependency of multipath components which are very important for UWB propagation channel. After including this frequency dependency of multipath components the modified channel impulse response can be written as:

$$h(t) = \sum_{i=1}^{N} a_i x_i(t) \otimes \delta(t - \tau_i)$$

Large Scale Fading: Wireless communication channels are random in nature to analyze their characteristics and predict the possible change is not easy. In wireless channel radio waves propagate through three basic mechanism called reflection, diffraction and scattering. Since open air contains so many stationary and dynamic objects so the waves travels along different path, which causes to decrease in signal strength. When this happens for short transmitter receiver distance it is called as small scale fading and when the distance between transmitter receivers is the order of several thousands of meters then decrease in signal strength is due to large scale fading [26].Small scale fading happens because; received signal is a combination of multipath components which are delayed version of original signal with random phases. Large scale fading is the attenuation of signal due to obstacles in propagation path over a long distance [10]. In large scale propagation model waves propagated by following three mechanisms:

Reflection: It is the change in direction of radio wave when it impinges upon interface between two different mediums in such a way that incident waves return to the same medium from which it is coming [27]. For reflection to occur dimension of obstacles should be very large when compared with wavelength of propagated radio wave [26].

Diffraction: Diffraction is the phenomena in which electromagnetic wave spreads out after striking the surface which has sharp edges or by passing through a narrow aperture. A secondary wave generated behind the obstacle, which cause bending of transmitted wave around the obstacle [26]. Here for diffraction, size of obstacle or gap should be same as the wavelength of electromagnetic wave.

Scattering: Scattering means the dispersion of electromagnetic wave into various direction, when it passes through a medium which consist of objects with dimension very small than the wavelength of transmitted wave. Scattered wave produces by rough surfaces, small particles and other irregularities in channel [26].

5.5. Ray theory model of propagation

Path loss is a very important parameter for designing a wireless channel, as it used to evaluate large scale fading effect which in turn determines the small scale fading characteristics of the channel. Path loss plays an important role in link budget analysis which calculates the attenuation over the travelled distance and also cost of transmission. Path loss can be modelled from power law dependence with distance from transmitter $L_p = ad^{\gamma}$and to accommodate the shadowing phenomena, a random variable with log normal distribution added to the average path loss which takes care of fading effect [27]. Usually the path loss frequency dependence is ignored while modelling a UWB propagation channel because it has negligible effect over the frequency range of current wireless communication systems. But this assumption cannot be applied universally to UWB systems. So here it is intended to study the two ray model for path loss over short ranges [27]. Since the available conventional narrowband plane earth model are not useful so two ray link is evaluated for as a function of both frequency and distance. Considering the specific UWB application for railway tunnel, the analysis is carried out up to the distance of 55 meters within the operational frequency range of 3.1 GHz to 10.6 GHz.

According to definition a two ray propagation model contains the direct ray and the ground reflected ray, as illustrated in figure below:

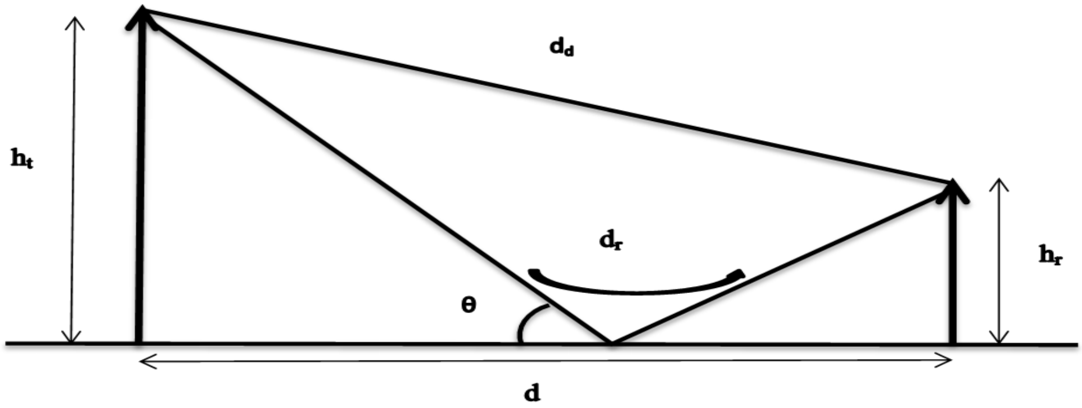


Figure 5.1 The two ray propagation model

Where, h_t *and* h_r are the height of transmitter and receiver respectively.

Direct ray and ground reflected ray represented by d_d and d_r respectively and d is the separation between transmitter and receiver. Actual practical channel model contains several multipath components but the basic analysis of considered channel model will be done on the basis of this above said two ray theory. By considering that received electric field is the result of superposition of two rays and path loss is expressed as $L_p = G_p^{-1}$ where path gain G_p is represented as [27].

$$G_p = \left(\frac{\lambda}{4\pi}\right)^2 * [(e^{-jkd_d}/d_d) + (R_{H,V}e^{-jkd_r}/d_r)]^2$$

Where,

$$k = \frac{2\pi}{\lambda}, \qquad \lambda = \frac{c}{f} \qquad \text{c = speed of light}$$

Length of rays for line of sight and non-line-of-sight is derived from the figure above by considering the image theory:

$$d_d = \sqrt{d^2 + (h_t - h_r)^2}$$

And

$$d_r = \sqrt{d^2 + (h_t + h_r)^2}$$

Fresnel reflection coefficients for horizontal and vertical polarization are defined as:

$$R_H = \frac{sin\theta - \sqrt{\epsilon_r - cos^2\theta}}{sin\theta + \sqrt{\epsilon_r - cos^2\theta}}$$

And

$$R_V = \frac{\epsilon_r \, sin\theta - \sqrt{\epsilon_r - cos^2\theta}}{\epsilon_r \, sin\theta + \sqrt{\epsilon_r - cos^2\theta}}$$

Where

$$\varepsilon_r(f) = \varepsilon_r(f) - j\frac{\sigma(f)}{2\pi f \varepsilon_0}$$

The above equation is for dielectric constant of the reflecting surface, for appropriate characterization of UWB propagation it is must to consider the frequency dependency of relative permittivity $\in_r' \ (f)$ and the conductivity $\sigma(f)$ over the UWB frequency range.

5.6. Communication system model

Any communication system consists of three basic components transmitter, receiver and most important one channel. Here it is a communication system setup for railway signalling and control system by using UWB technology. Both the small scale fading and large scale fading effect for UWB signal propagation are discussed considering railway tunnel as an oversized waveguide in which message signal propagated by multiple reflection gives rises to multipath components. Ultra wideband communication system can be classified as pulse based or multicarrier based communication [29]. Multicarrier based UWB system uses OFDM technique, with orthogonal carriers like modified Gegenbauer polynomial, modified Hermite polynomial for data transmission [30] and [31]. Here the thesis is mainly focusing on carrier less UWB system, so it will consider the single link UWB communication system for the sake of simplicity. The basic block diagram for UWB communication system for railway tunnel is shown in figure below:

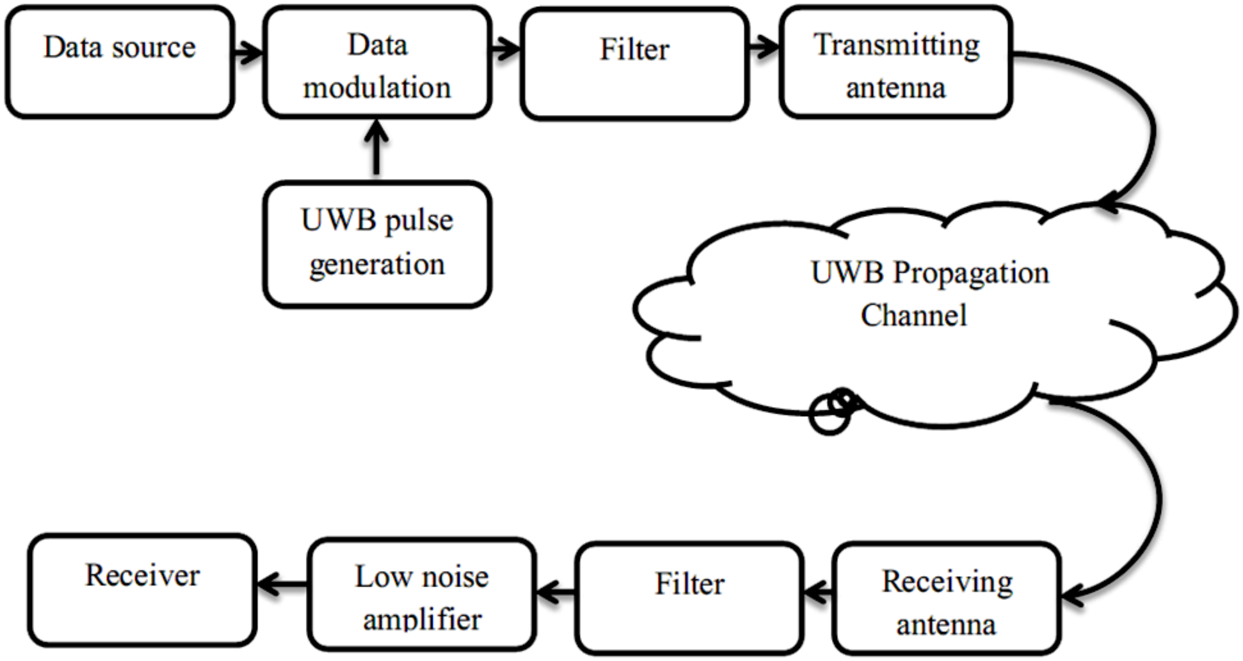


Figure 5.2 UWB Communications system model [5]

Figure above shows a complete communication system with all necessary components i.e. transmitter, receiver and wireless channel. Transmitter consists of source of data, UWB modulator, UWB signal generation and other basic part like filter and antenna array. Modulation is needed because one single UWB pulse does not contain any information so to add digital information to it by means of some modulation techniques [27]. Several methods of modulation are available which are classified as time based techniques and shape based techniques, Pulse position modulation (PPM), delayed or sent in advance each pulses at regular time interval, so binary communication can be performed with forward and backward shift in time. Bi-phase modulation (BPM) or more specific binary phase shift keying (BPSK) converts the pulses into opposite phase, while in on-off keying (OOK) absence (0) or presence (1) of pulses defines the digital information. Pulse amplitude modulation (PAM) varies the amplitude of pulses to transmit the digital information [27]. One more advanced modulation technique is orthogonal pulse modulation (OPM) which is also a type of pulse shape modulation with the characteristics that pulse shapes are orthogonal to each other.

OPM is used for multiple accesses in UWB communication system [28]. Here the modulated data transmitted through a wireless channel. It is assumed that the railway tunnel as multipath channel with added white Gaussian noise, and has already discussed about UWB propagation characteristics i.e. small scale fading and large scale fading effect. The considered channel is frequency selective in nature. At the receiving it consists of a filter, a low noise amplifier and a receiver. UWB signal is mainly detected by correlator receiver or Rake receiver. Correlator receiver is a set of multiplier and integrator which compares the received signal with the reference signal and tells about how much it resembles the original transmitted signal. Rake receiver consists of several branches of correlator. Since UWB channel suffers from multipath fading so rake receiver is used to improve the reception quality by adding up these multiple versions of transmitted signal in a constructive way. But it increases the complexity of circuitry.

5.7. UWB channel model

In UWB communication system accurate designing of channel model is a very important issue [27]. Indoor and outdoor channel modelling and propagation effects need to be carefully examine before implementation of UWB systems. Channel models should provide facility for calculation of large and small-scale statistics [17] and [33].

Specifically large-scale models are necessary for network planning and link budget design and small-scale models are necessary for efficient receiver design. The most famous multipath UWB indoor channel models are **Tap-delay line Rayleigh fading** model, **Saleh and Valenzuela (S–V)** model and **Δ-K** model. The S–V channel measurement shows that the multipath components are arriving in a cluster form [34]. The different paths of such wide band signal can give rise to several multipath components, all of which will be part of one cluster.

5.7.1. Modified Saleh–Valenzuela Model

During 2002 and 2003, the IEEE 602.15.3 working group for WPAN, and specially its channel modelling subcommittee decided to use the so called modified Saleh- Valenzuela model (S-V) as a reference for UWB channel model (Foerster, etal. 2003; Forester 2003) [32]. The real valued model is based on the empirical measurements originally carried out in indoor environments in 1987 (Saleh and Valenzuela, 1987). Due to the clustering phenomena observed at the measured

UWB indoor channel data, the model proposed by IEEE 802.15 is derived from Saleh and Valenzuela using a log-normal distribution rather than an original Rayleigh distribution for the multipath gain magnitude.

In the S-V models, both the cluster and ray arrival times are modelled independently by Poisson processes. The phase of the channel impulse response either 0 or π. Therefore, the model contains no imaginary component;

$$h_i(t) = X_i \sum_{l=0}^{L_C^{-1}} \sum_{k=0}^{K_{LC}^{-1}} \alpha_{k,l}^i \delta(t - T_l^i - \tau_{k,l}^i)$$

Where α^i_k represents the multipath gain coefficients, T^i_l the delay of the l^th^ cluster, $\tau_{k,l}^i$ gives the delays for K^th^ multipath components relative to the l^th^ cluster arrival time (T^i_l). Shadowing effect is log-normal distributed and is represented by x_i and i refers to the i^th^ realization. The proposed modified Saleh- Valenzuela model uses the following definitions:

- ✓ T_l = the arrival time of the first phase of the l^th^ cluster;
- ✓ $\tau_{k,l}$ =the delay of the k^th^ path within the l^th^ cluster relative to the first path arrival time, T_l;
- ✓ Λ = cluster arrival rate;
- ✓ λ = ray arrival rate, i.e., the arrival rate of path within each cluster.

The definition assumes that $\tau_{0,l} = 0$. The cluster arrival time distribution can be presented by (Foerster, 2003).

$$P(T_l/T_{l-1}) = n\, exp[-n(T_l - T_{l-1})], \qquad l > 0$$

And the arrival times by

$$p\left(\tau_{k,l} \downarrow \tau_{(k-1),l}\right) = \lambda \exp\left[-\lambda\left(\tau_{k,l} - \tau_{(k-1),l}\right)\right], \mathrm{k} > 0:$$

The channel coefficients are defined by (Foerster, 2003)

$$\alpha_{k,l} = P_{k,l}\xi_l\beta_{k,l}, \quad and$$

$$20log_{10}\left(\xi_l\beta_{k,l}\right) \alpha \mathrm{N}(\mu_{\mathrm{k,l}}\sigma_1^2 + \sigma_2^2) \quad or$$

$$\left|\xi_l\beta_{k,l}\right| = 10^{(\mu_{\mathrm{k,l}}+\mathrm{n}_1+\mathrm{n}_2)/20}$$

Where $n_1 \alpha\ N(0,\sigma_1^2)$ and $n_2 \alpha\ N(0,\sigma_2^2)$ are independent and corresponds to the fading on each cluster and ray, respectively and

$$E\left[\left|\xi_l \beta_{k,l}\right|^2\right] = \Omega_0 e^{-T_1/\Gamma} e^{-\tau_{k,l}/\gamma}$$

Where Ω_0 the mean energy of the first path of the first cluster, and $P_{k,l}$ is equi-probable {-1, +1} to account for the signal polarity inversion due to the reflections. The $\mu_{k,l}$ is given by (Foerster, 2003)

$$\mu_{k,l} = \frac{10\ln(\Omega_0) - \frac{10T_1}{\Gamma} - 10\tau_{k,l}/\gamma}{\ln(10)} - \frac{(\sigma_1^2 + \sigma_2^2)\ln(10)}{20}$$

The variables in the above equations represent the fading associated with the l^th^ cluster, ξ_l, and the fading associated with the k^th^ ray of the l^th^ cluster $\beta_{k,l}$.

As noted above the impulse responses given by the model are real valued. Due to the fact that the log- normal shadowing of the total multipath energy is captured by the term x_i, total energy contained in the terms $\{\alpha_{k,l}^i\}$ is normalized to unity for each realization. The shadowing term is characterized by (Foerster, 2003).

$$20\ log10\ (X_i) \alpha\ N(0,\sigma_x^2)$$

The model derives the following channel parameters as an output:

- ✓ Mean and root mean square (RMS) excess delays;
- ✓ Number of multipath components;
- ✓ Power decay profile.

In addition to cluster and ray arrival rates, Λ & λ the model inputs cluster and ray decay factors, Γ & γ, respectively, and standard deviation terms in dB for cluster log- normal fading, ray log- normal fading and log- normal shadowing term for total multi-path realization σ_1, σ_2 and σ_3 respectively.

Four different channel implementations are suggested, which are based on the average distance between transmitter and receiver, and whether a LOS component is present or not.

Target channel characteristics	**SV-1**	**SV-2**	**SV-3**	**SV-4**
Mean excess delay	5.05	10.38	14.18	
RMS delay		8.03	14.28	25
NP	5.28		35	
NP(85%)	24	36.1	61.54	
Model parameters				
Λ (1/nsec)	0.0233	0.4	0.0667	0.0667
λ (1/nsec)	2.5	0.5	2.1	2.1
Γ	7.1	5.5	14.00	24.00
γ	4.3	6.7	7.9	12
σ_1 (dB)	3.3941	3.3941	3.3941	3.3941
σ_2 (dB)	3.3941	3.3941	3.3941	3.3941
σ_3 (dB)	3	3	3	3
Model characteristics				
Mean excess delay (nsec) (τ_{m})	5.0	9.9	15.9	30.1
RMS delay (nsec) (τ_{rms})	5	8	15	25
NP$_{10dB}$	12.5	15.3	24.9	41.2
NP(85%)	20.8	33.9	64.7	123.3
Channel energy mean (dB)	-0.4	-0.5	0.0	0.3
Channel energy standard (dB)	2.9	3.1	3.1	2.7

Table 5.1 The four channel models and their parameters [32]

The arrival of multipath components is modelled by using Poisson distribution and thus the inter arrival time between multipath components is based on exponential distribution. The multipath arrival of UWB signals are grouped into two categories: cluster arrival and ray arrival within a cluster. This model requires several parameters to describe indoor channel environments [35]. Ray arrival rate is the arrival rate of path within each cluster. The cluster arrival rate is always smaller than the ray arrival rate. The amplitude statistics in S–V model are based on lognormal distribution, the power of which is controlled by the cluster and ray decay factor[36]. Indoor channel environments are classified as CM1, CM2, CM3, and CM4 following IEEE 802.15.3a standard based on propagation conditions as follows [37].

- CM1 describes a line-of sight (LOS) scenario with a maximum distance between transmitter and receiver of less than 4m.
- CM2 describes the same range as of CM1, but for a non-line-of sight (NLOS) situation.
- CM3 describes a NLOS medium for separation between transmitter and receiver of range 4-10m.
- CM4 describes an environment of more than 10m with strong delay dispersion, resulting in a delay spread of 25ns with NLOS medium.

NP_{10dB} → number of paths within 10dB of the peak
NP (85%) → number of paths capturing 85% of the energy
CM → stands for channel model.

The average profiles are calculated from 100 independent channel realizations, which is the approach recommended by the IEEE 802.15., the delay resolution in the model is 167 ps. In this research work it is to design UWB based communication system model for railway tunnels specifically for the AA-LRT tunnel at piassa (Giyorgis). Main problems associated with tunnel environment are heavy multipath, frequency selectivity and distance dependent path loss, so I cannot be simply implemented. It needs to consider the geometrical ray model for UWB propagation [1].

The impulse responses of the four different modified S-V models are shown in Figure below. It is apparent that paths in CM1 and CM2 tend to concentrate in two or three clusters with smaller delay, whereas in CM3 and CM4 paths tend to spread over more clusters and have bigger delay. This is due to their different cluster arrival rates. And the gains of paths in CM3 and CM4 decay faster due to their longer path [19].

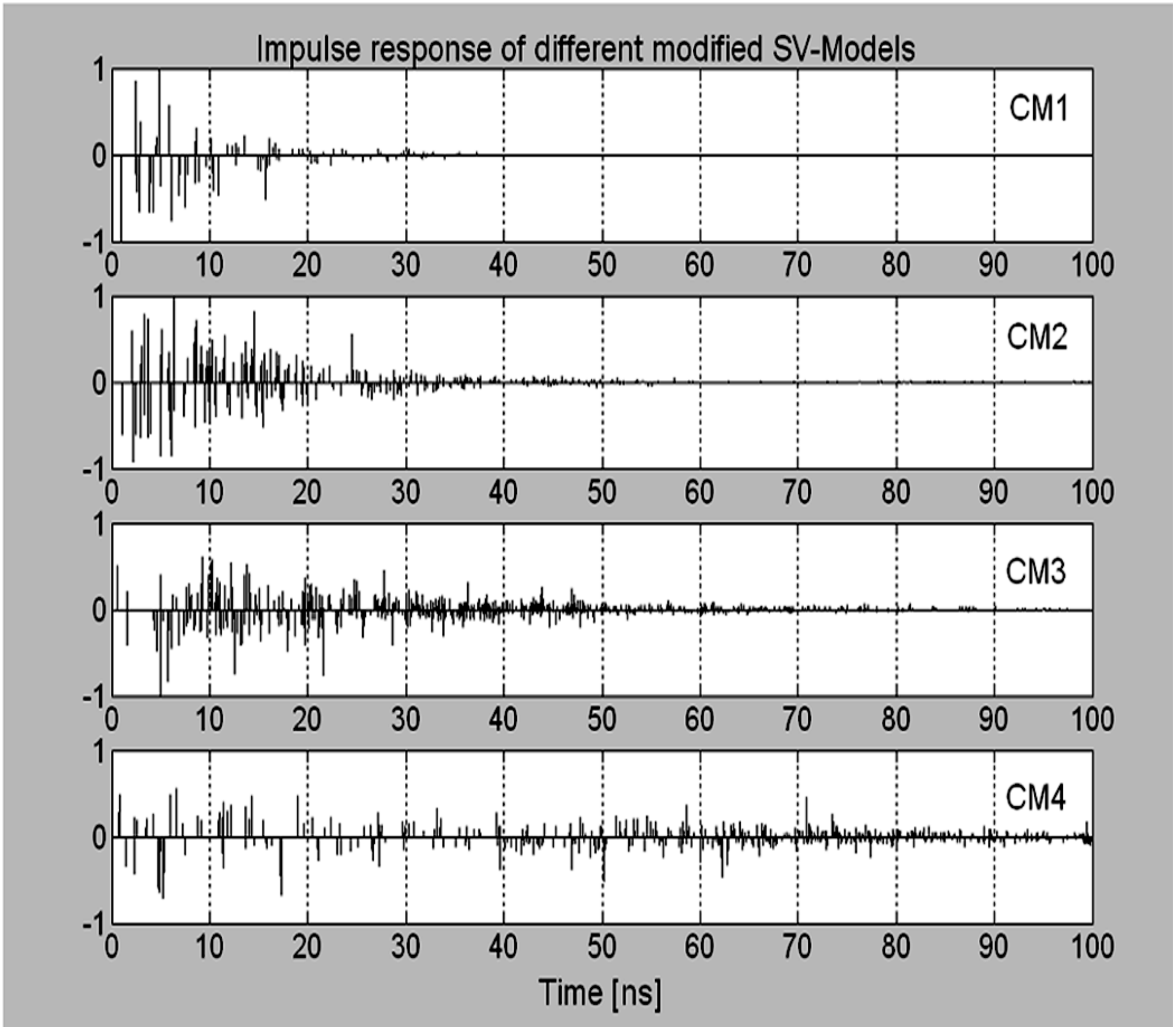


Figure 5.3 Delay profiles for Modified Saleh-Valenzuela channel CM1-4 [19]

5.8. Summary

This chapter concludes the requirements to design an UWB radio based wireless communication system for railway tunnel. It explained the two important UWB channel characteristics i.e. multipath propagation and large scale fading, designed channel going to be analyzed on the basis of these two characteristics. It described the ray theory model of propagation with their necessary mathematical descriptions.

Chapter 6

SIMULATION AND RESULTS

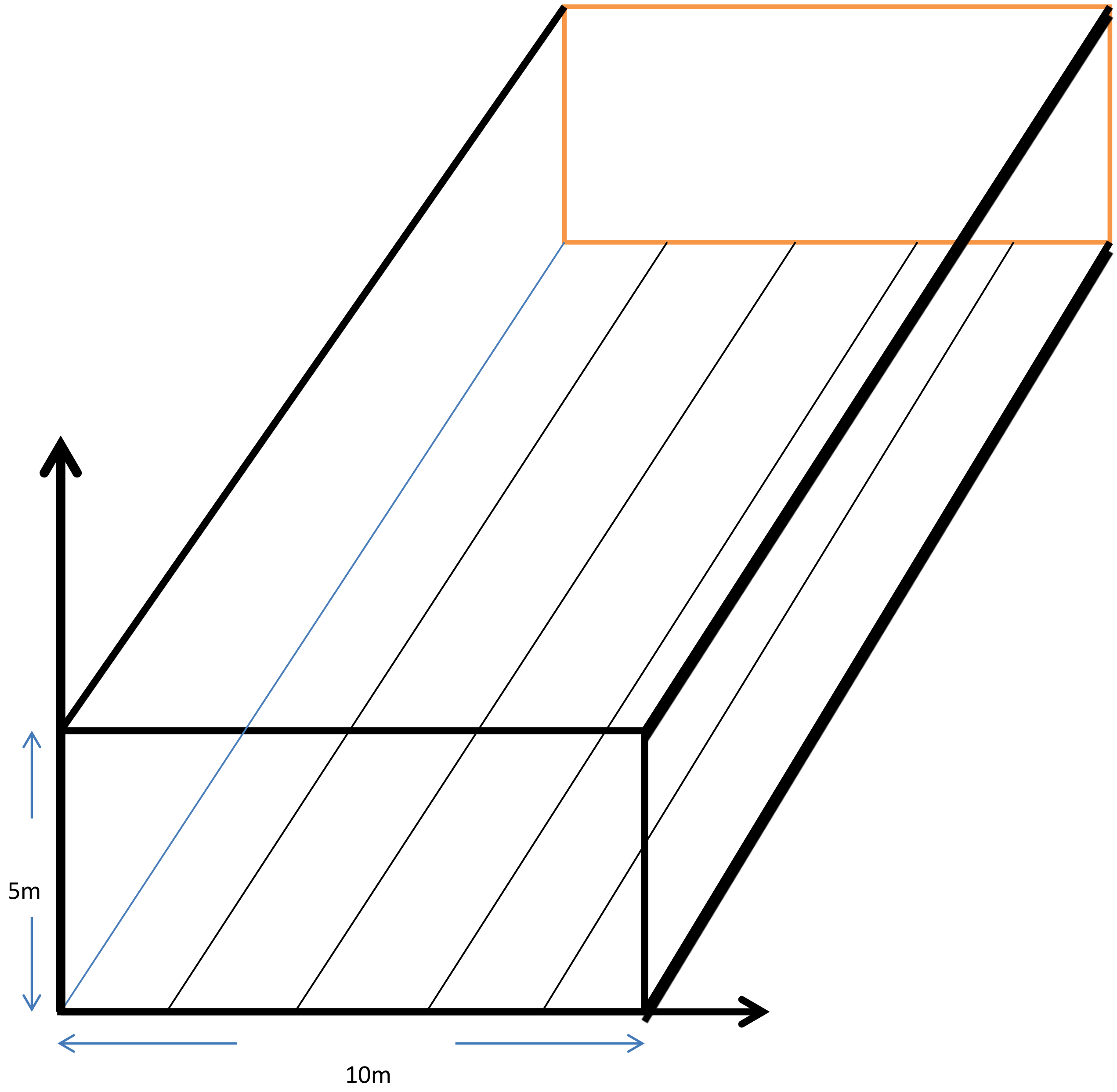


Figure 6.1 tunnel model

6.1. Model of UWB propagation channel for tunnel

Modern railway transportation is mainly operated under tunnel. Tunnel environment provides severe attenuation to the narrowband communication system as it suffers from frequency selectivity, heavy multipath due to reflections from the surfaces of tunnel and signal attenuation along the tunnel depending on the distance between transmitter and receiver and used frequency [3], [5] and [8].So UWB radio communication has the capability to perform well under above said situations because of its very large bandwidth. Rectangular shaped tunnel is considered as an oversized waveguide because tunnel size is much large in comparison with operating wavelength. The basic ray theory model has been considered to evaluate the channel responses. The tunnel can be look as a multipath channel with added white Gaussian noise. It is assumed that channel is static and time invariant since it considers the short distance propagation. So

$$h(t) = \sum_{i=1}^{\mathrm{N}} a_{\mathrm{i}} \exp(j\theta_{\mathrm{i}})\delta(t-\tau_i)$$

Where;

a_i is the amplitude of ith path
τ_i is the delay of ith path
θ_i is the phase value of ith path
N is the number of resolvable multipath

This research includes the theoretical study of tunnel channel model considering it as deterministic in nature over the UWB frequency range of 3.1 GHz to 10.6 GHz. So the equivalent channel impulse response and the frequency response has been evaluated by using following equations [8].

$$E_{tot} = \sum_{f_{min} f_{max}} E_0 \frac{\lambda}{4\pi} \sum_{n=0}^{N-1} \frac{e^{-jkd_n}}{d_n} R_v^{\alpha} R_H^{\beta}$$

$$h(t) = F^{-1}\{\frac{E_{tot}}{E_0}\}$$

Where,

E_0= reference electric field

N= Number of resolvable multipath

k= wave number

$R_{V(H)}$= complex reflection coefficient on vertical(horizontal wall)

α(β)= number of reflections on the vertical (horizontal wall)

d_n=length of n^{th} ray

Channel characteristics have been studied by considering the following theoretical model and simulation setup shown below. The transmitter is located at a particular place along the main axis of the tunnel. The receiver moves along the length of the tunnel from a reference distance (1 m) then starting from 5 m up to a given distance $\boldsymbol{d_n}$. Here channel parameters estimated in the 3-10 GHz frequency band [8].

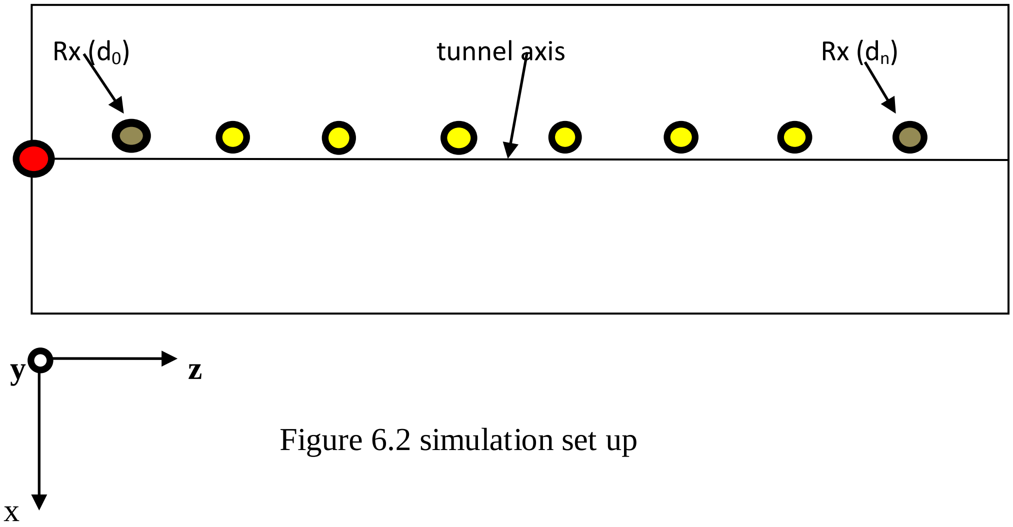


Figure 6.2 simulation set up

Parameter	Value
Frequency band	3.1-10.6 GHz (1601 samples)
Conductivity (S/m)	$\sigma = 0.05$
Permeability (H/m)	$\mu_r = 1$
Permittivity (F/m)	$\varepsilon_r = 7$
Tunnel size (b*a) (m)	5*10
Number of reflections(vertical wall)	$\alpha = 12$

Number of reflections (horizontal wall)	$\beta = 10$
N (number of multipath component)	168+ direct path

Table 6.1 Tunnel parameters and their used values in the simulation

6.2. Wave propagation through channel

As mentioned before, that railway tunnel is considered as a multipath channel with additive white Gaussian noise. Now the designed multipath channel's behavior is analyzed by propagating three UWB pulse shapes and then observing the effect on the shape of transmitted waveforms. Three different UWB wave shapes considered here are Gaussian impulse, Gaussian mono-pulse and truncated sinusoidal pulse, propagated through the channel without using any kind of modulation techniques, for four (1m, 5m, 25m & 55m) transmitter-receiver distances. By comparing transmitted and received pulses, time delay and phase delay provided by channel are calculated.

6.3. Channel performance based on bit error rate

The small scale fading effect and path loss has been studied for the channel. Now for the same four different distances between transmitter and receiver, bit error rate performance has been evaluated over the considered channel model. While choosing modulation technique consider various criteria like data rate, simple to implement, immunity to interference and error performance [3]. So by keeping in mind all this criteria it is selected BPSK modulation as it requires less energy per bit and work effectively for weak SNR values. BER versus SNR graph has been plotted shown in figure 6.9. Figure shows four BER plots for 1m,5m, 25m and 55m transmitter receiver separation. Because of distance dependent path loss and small scale fading effect degradation in channel performance is easily observable. For the distance up to 25 meter considered UWB channel shows acceptable performance while increasing distance UWB channel performance start to degrade, because strength of electric field start to decreases rapidly along with distance. So it is concluded that UWB communication system for railway gives very good performance for shorter distances and to cover the larger distances it needs to use intermediate equipment which could maintain the level of transmission and reception.

6.4. Results

Figure 6.3 shows the small scale fading characteristics of the considered UWB channel model over a distance of 15 meter inside a tunnel, it clearly shows that the strength of signal changes rapidly over the UWB frequency range for different Tx-Rx distance. For short distances fades are fast and frequent as number of multipath components received at receiver increases but as it is gone for longer distance fades become less frequent because number of constructive rays decreases at receiver side, and hence strength of electric field decreases [3]. It shows that UWB channel gives best performance for short ranges but as the receiver go higher in distance due to the frequency selectivity property and path loss, the channel response gets attenuated. Figure 6.4 shows the corresponding channel impulse responses, which is a set of impulses due to multipath components; effect of distance is also clearly shown in the figure over the impulse strength. Figure 6.5 shows the average path loss over the entire frequency band, which is calculated by following equation[5].

$$PL(d) = \frac{1}{M}\sum_{i=1}^{M} |H(f_i, d)|^2$$

$H(f_i,d)$ is channel frequency response, M is the number of frequency components at used frequency band, channel frequency response is considered as

$$H(f, d) = K_H \frac{\lambda}{4\pi d} exp(-ikd)$$

Some standard UWB wave shapes propagated through this modelled channel are shown in figure 6.6, 6.7, and 6.8. Since the considered channel behaves as multipath channel so it needs to study that how much phase shift and time shift it provides to these standard UWB waveforms. Values of phase shift and time shift is shown in the table 5.2. Figure 6.9 shows the bit error rate versus signal to noise ratio plot for the considered UWB channel using BPSK modulation technique for four different transmitter receiver distances. Figure 6.10 shows the comparison of bit error rate versus signal to noise ration plot for binary phase shift keying modulation and on-off keying modulation techniques. It clearly shows that BPSK gives better BER performance than orthogonal modulation techniques like OOK.

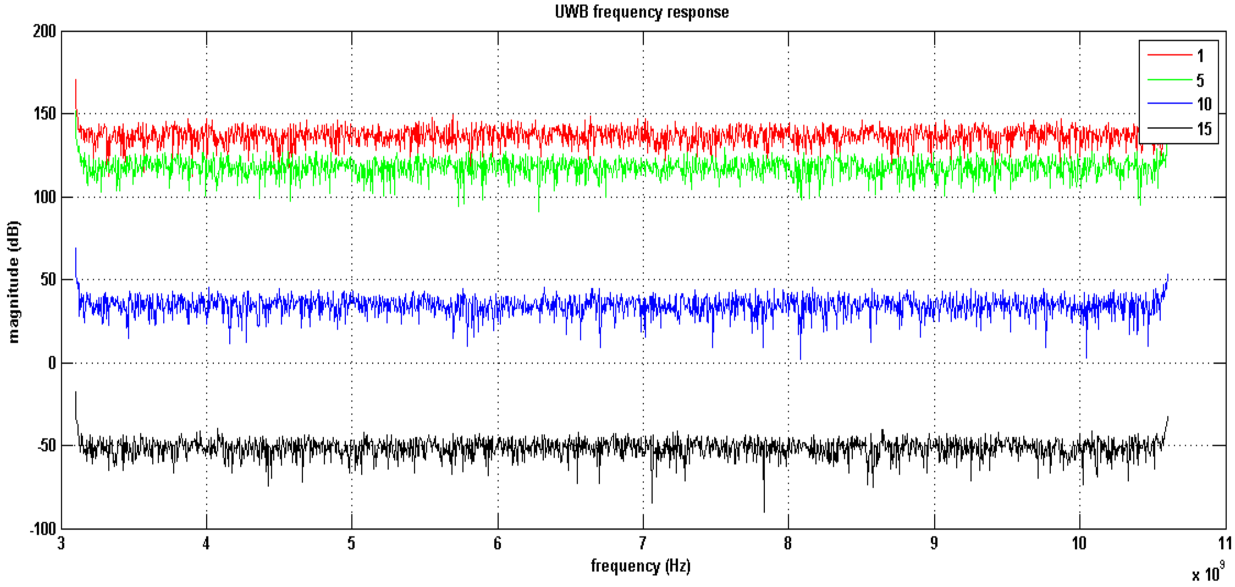


Figure 6.3 UWB Frequency Responses for variable distances between Tx and Rx

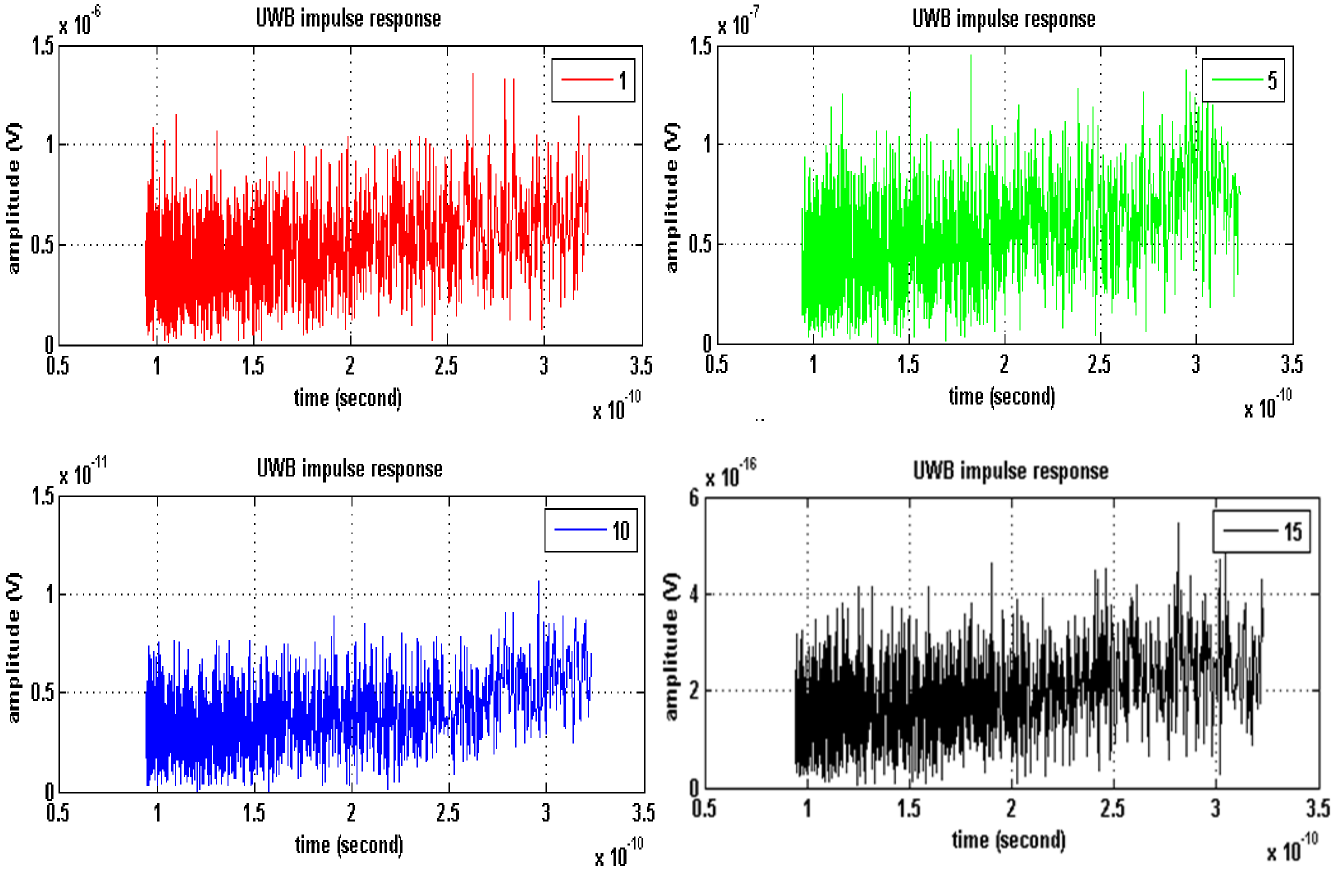


Figure 6.4 Corresponding Channel Impulse Response

Above figures are the frequency and impulse responses of the modelled channel inside tunnel. Channel frequency response is plotted for strength of received electric field versus frequency, for 1m, 5m, 10m and 15m transmitter receiver distance. Different distances considered because receiver is moving inside tunnel as it is mounted over the train. So with increase in distance the electric field strength starts to decrease from the level of 150dB to the level of -50dB. Multipath fading is the reason for this attenuation in signal strength. Channel impulse response is plotted for amplitude of impulse versus time. Impulse response plot also shows that amplitude of impulses reduces from the order of 10^{-6} volt to the order of 10^{-16} volt with increasing distance.

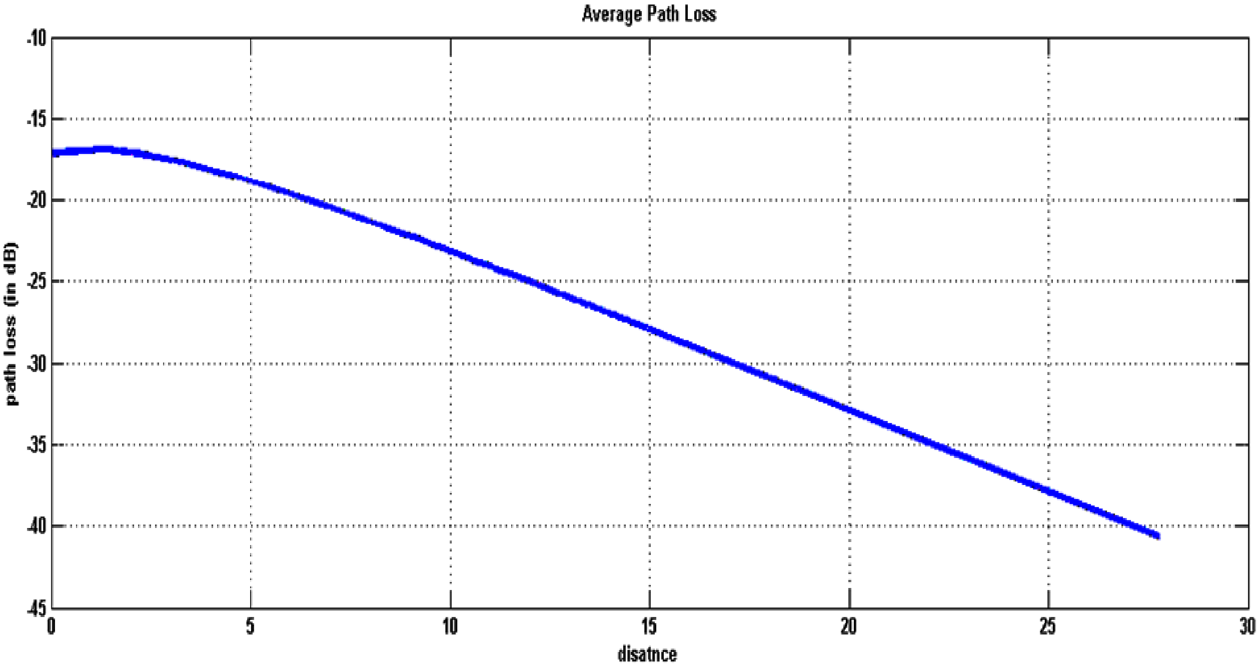


Figure 6.5 Average Path Loss

Above plot shows the distance dependent path loss averaged over UWB frequency band over the communication ranges of 1 to 600 meters[8]. Plot shows that for the first 100 meters distance path loss value decreases by 16 dB than from next 100 meter onwards it decreases approximately by 5 dB.

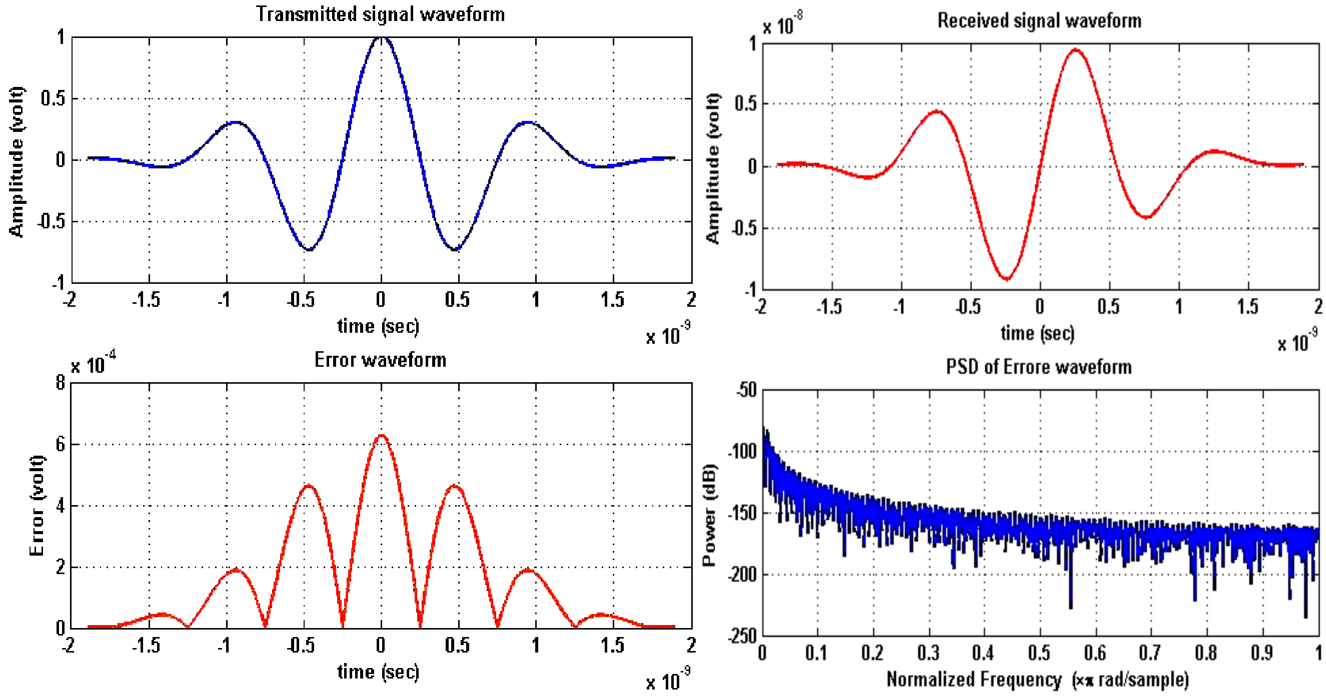


Figure 6.6 Gaussian impulse

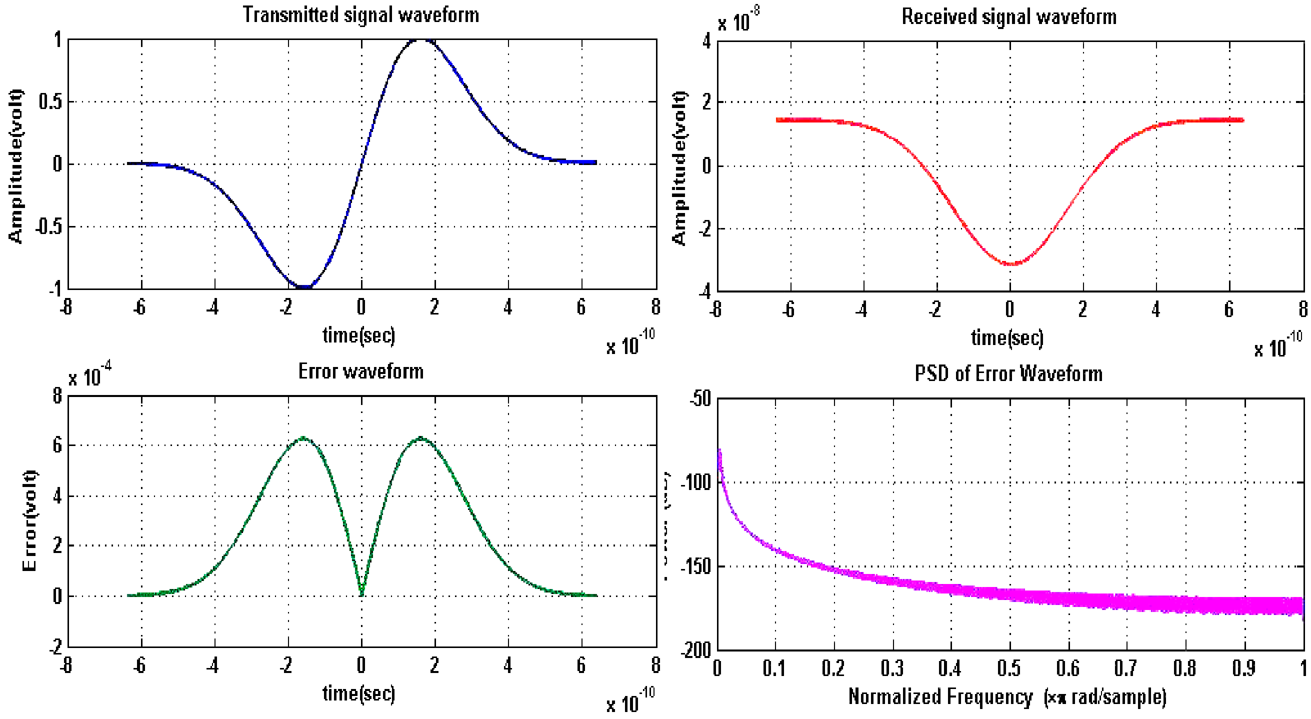


Figure 6.7 Gaussian Mono-pulse

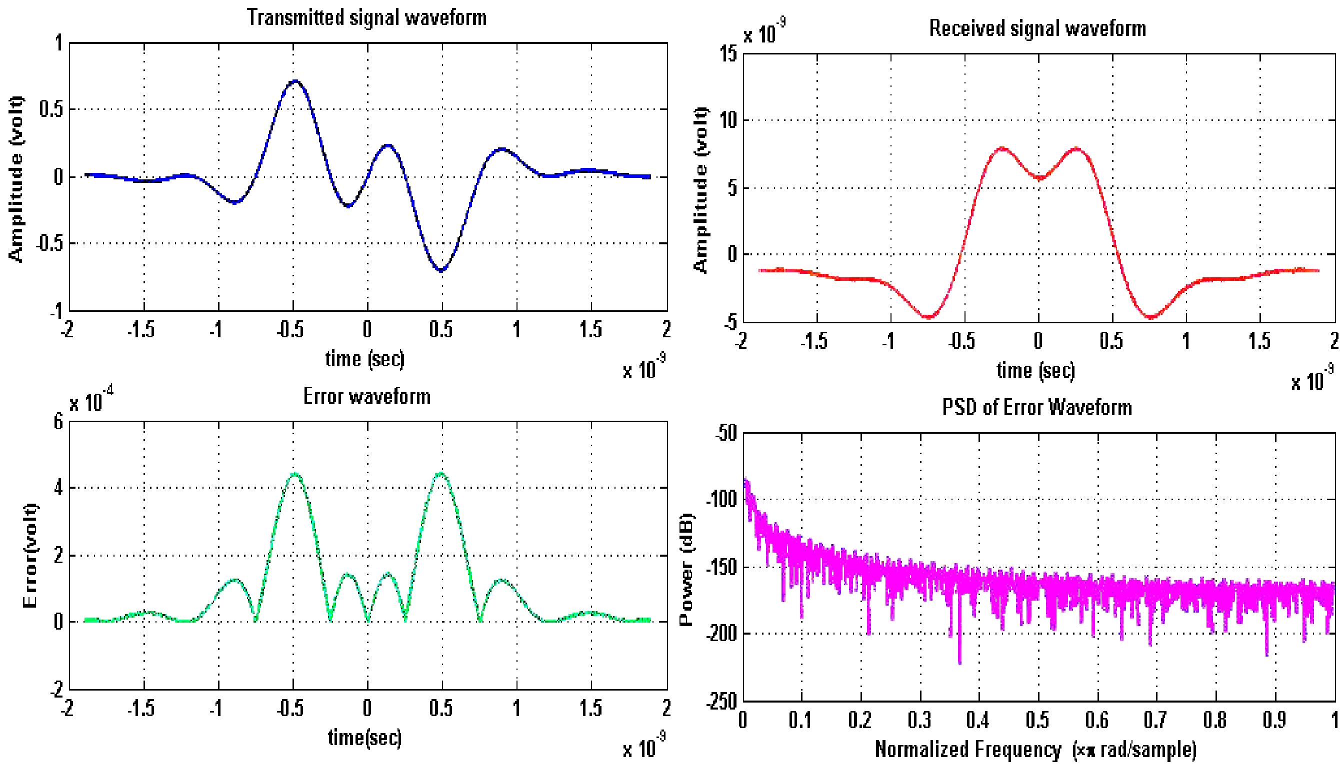


Figure 6.8 Truncated Sinusoidal Pulse

Figure 6.6 to 6.8 shows plots for transmitted and received pulses over the channel. It shows that modelled channel provide the phase shift and time shift to the propagated waveforms, this is a basic property of multipath channel. Time shift and phase shift calculated for 1m, 5m, 25m and 55m distances with Gaussian pulse, Gaussian mono-pulse and truncated sinusoidal pulse. It is summarized in the table 6.2, from which it can be observed that among all, up to the distance of 25 meter Gaussian impulse faced less delay in both phase and time in comparison with Gaussian mono-pulse signal, while truncated sinusoidal signal faces advancement in phase and time. Power spectral densities shows that power spreads in the range of -100 dB to -200 dB over the UWB frequency band. Variations in PSD for all type of wave shapes are almost same because all are based on Gaussian pulse.

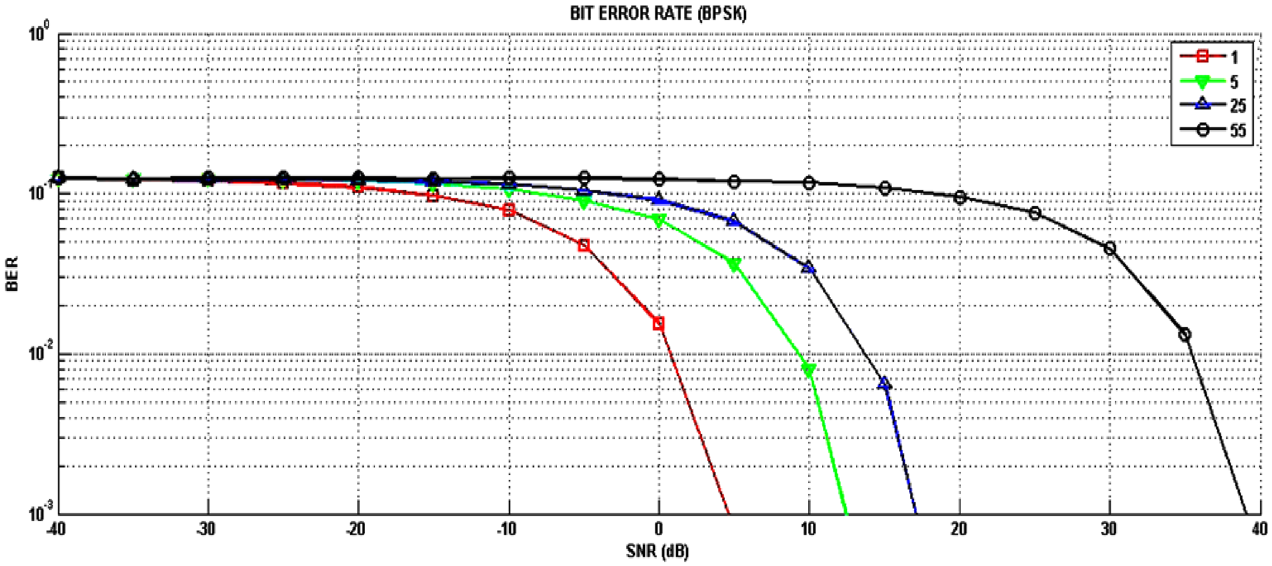


Figure 6.9 Bit error rate performance for UWB channel

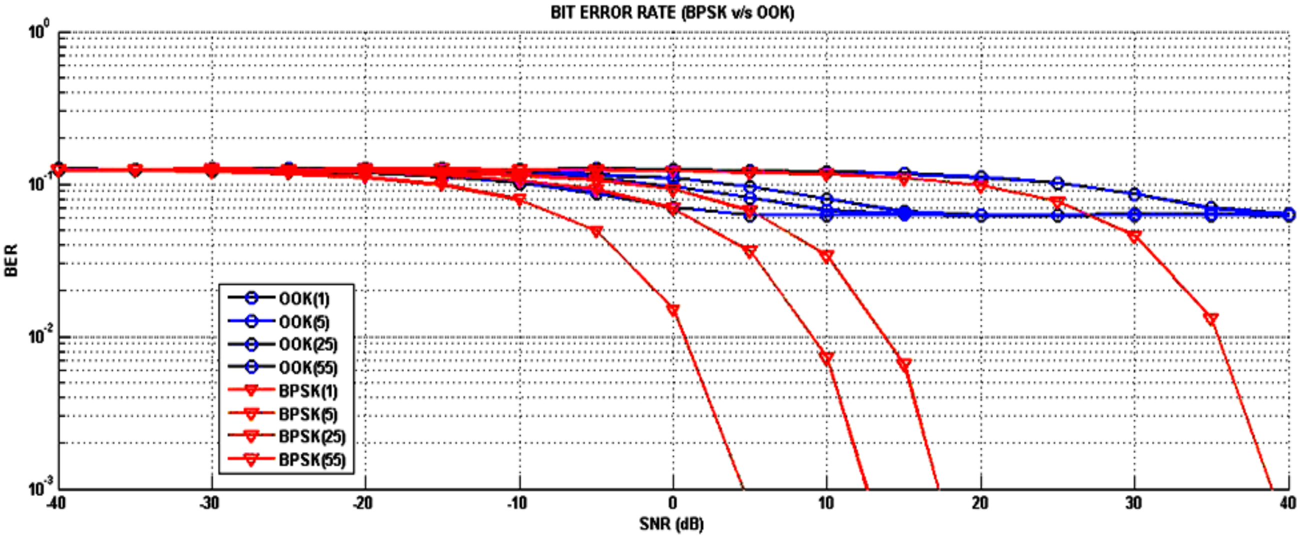


Figure 6.10 Comparison of BER for BPSK and OOK modulation

Figure 6.9 and figure 6.10 shows the plot for bit error versus signal to noise ratio up to the distance of 55 meter. Figure 6.9 shows the BER performance of modelled channel with binary phase shift keying modulation. It contains four plots for four different distances through which it is observed that with increasing distance BER performance degraded because of multipath fading and distance dependent path loss. To maintain the BER value of 10^{-3}, increase in SNR value with distance is shown below:

Distance (m)	Distance (m) SNR (dB)
1	5
5	13
25	17
55	39

Table 6.3 Distance versus SNR (BER = 10^{-3})

Figure 6.10 shows the BER comparison between BPSK and OOK modulation techniques. Bit error rate performance for BPSK is better than OOK, as BPSK is a bi-phase modulation technique and distance between two bits are more than in OOK technique, so it is more immune to the interferences.

6.5. Summary

This chapter presented the details about mathematical descriptions of the problem, simulations done on the basis of these mathematical description and simulation setups. Channel characteristics analyzed by evaluating frequency response, impulse response and path loss. Effect of channel over three standard UWB pulse shapes observed. Bit error rate performance evaluated for BPSK and OOK modulation techniques

Chapter 7

CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

7.1. Conclusion

A new promising technique adopted by communication community due to its best performance achievements is Ultra wideband technology which offers a solution for high bandwidth, high data rate, low cost, low power consumption, position location capability, resilience to multipath fading etc. These benefits of UWB motivate to apply it for railway transportation. So it is possible to get faster and safer mode of transportation. To implement this new wireless technology the most critical portion of railway network, railway tunnel for AA-LRT at piassa Giyorgis is chosen, as inside tunnel existing narrow band wireless communication system gets highly attenuated. To design an effective UWB communication system for railway tunnel, it is must to understand the UWB propagation characteristics in tunnel. Tunnel represented as an oversized waveguide and ray theory model of propagation used. The tunnel is assumed as multipath fading channel with additive white Gaussian noise. So the effect of small scale fading and path loss evaluated up to the distance of 55 meter. Bit error rate performance evaluated to test the quality of reception. Thesis work done to design UWB based radio wireless communication system for railway tunnel, is concluded under following core points:

- UWB is immune to multipath fading and path loss over a short distance of about20 meters. It is also well known that UWB has very high speed within this range of the order of >100Mbps.
- Effect of fading over the channel response is that the strength of electric field and amplitude of impulses start decreasing with distance. It is because with increasing distance possibility of receiving multipath components in constructive way decreases.
- The bit error rate performances get degraded due to multipath fading effect which is evaluated for the extended distance of 55 meter.
- Comparison of BER for BPSK and OOK modulation techniques shows that BPSK is more immune to interference in comparison with OOK. It is because BPSK modulates

the bits into two opposite phases (1 and -1) which results more separation between two consecutive modulated bits.

So UWB radio wireless communication has a very great potential to provide high speed data streaming over short range which makes possible to establish a fast and reliable communication system to control the train inside railway tunnel.

7.2. Recommendation for future work

As a scope of future work, with this much high data rate of UWB systems, driver less subway transportation system can be established in which both voice and video data transmission will possible. This research work is proposed for rectangular shaped railway tunnel only so the study can be extended for other railway tunnel geometries. Also in this work some factors in the channel modeling (like objects in the tunnel, number of peoples/passengers standing or moving in the tunnel [45]) are not included due to some limitations in conducting the research thus it is recommended to include these factors and improve the model for better accuracy in further study.

Chapter 8

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