PERFORMANCE EVALUATION AND COMPARISON OF COHERENT AND INCOHERENT RECEIVERS UNDER ATMOSPHERIC TUBULENCE

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Abstract

Optical free space communication system faces the major challenge because of the atmospheric condition. Signals receive in the ground station using two different types of receivers (Coherent detection and Intensity Modulation and Direct Detection (IM/DD)). Coherent detection uses PIN photo detector in the receiver end to attain the more sensitivity of the receiver. It receives the input data as a carrier signal and the local oscillator signal is mixed with the received signal and down convert the carrier signal to an intermediate frequency signal. The Intensity Modulation direct detection uses the Avalanche photo detector in the receiver end to attain the more sensitivity. This detection receives the input signal as a carrier signal and it is directly demodulated at the receiver back into the original signal. Signals receive in the ground station from the aircraft will be affected by the various types of noise like shot noise, thermal noise, etc. The occurrence of noises in the coherent detection is not exactly same as the IM/DD. Some noise get varies according to the electrical circuit noise produced in the receiver side. By deriving the signal-to-noise ratio, the background noise occur in the desired signal can be calculated. One of the main goals would be to derive a Probability Density Function (PDF) of the Signal-to-Noise Ratio (SNR) of the each type of receiver to check the efficiency of the receivers. Transmitting the optical signal from aircraft will face some data loss problem due to atmospheric turbulence disturbances, to identify the loss arises in the transmitting signal will be done by using the probability error method. Bit Error Rate (BER) derivation will take place to calculate and to identify the data loss occurs in the received signal. The project deals with measuring the efficiency and sensitivity among those two optical receivers and to check the robustness between those receivers against scintillations (power fades and surges) effects. In this work performance of the coherent receiver and IM/DD receiver using APD is compared with the different system characteristics. Sensitivity and performance of both the receivers are calculated with the same fading vector. Signal to noise ratio and bit error rate are theoretically derived and numerically analyzed in the case of atmospheric turbulence. Numerical results predict the performance of both the receivers.
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## Abbreviations

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<thead>
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<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>FSO</td>
<td>Free-Space Optical Communication</td>
</tr>
<tr>
<td>IM/DD</td>
<td>Intensity Modulation and Direct Detection</td>
</tr>
<tr>
<td>APD</td>
<td>Avalanche Photodiode</td>
</tr>
<tr>
<td>PIN</td>
<td>Photo Intrinsic</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>AMF</td>
<td>Avalanche Multiplication Factor</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
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</table>
Chapter 1 - Introduction

1.1 Introduction

Free Space Optical is the feasible technology for transmitting a signal with high data rate and security [1]. But the major mission in FSO system is to overcome the impact of atmospheric turbulence. The effect of atmospheric turbulence will result in the intensity fluctuation of the received optical signal known as fading [2]. In analyzing the Optical receivers some of the receiver parameter value into account. In the system model the internal parameters include received optical power, receiver sensitivity, receivers lens diameter, wavelength, bandwidth, BER and receiver field of view and the external parameters are related to the atmospheric condition. The internal parameter values are different for coherent detection and IM/DD receivers [3]. This project deals with finding and comparing the sensitivity and performance of the coherent and IM/DD receivers in different receiver characteristics. Comparing the coherent and IM/DD receivers with the noise component under atmospheric condition. SNR is numerically calculated with the same fading vector for the IM/DD system using APD receiver and the coherent detection system using PIN photodiode. SNR is related to the receiver sensitivity and the sensitivity of the receiver should be high enough to attain the robustness. The impact of total receiver noise is taken into account for both the receivers to check the performance of the receiver. BER is one finest way to identify the performance of the receiver. Expression of the BER theoretically derived and numerically values are tabulated, and are also discussed.

1.2 Motivation

In real time scenario the signal transfer from the aircraft to optical ground station has an impact of an atmospheric turbulence. In optical receivers, evaluation of receives are done with different detection techniques, different photo detectors, different fading vectors and different noise levels, but evolution and comparison of the optical receiver using same distribution fading vector to check the performance of the optical receivers are never handled. By comparing this two receivers one can easily get to know the performance and sensitivity of coherent and IM/DD receivers with the same fading vector.
1.3 Research Question

1. How to calculate probability density function of the SNR with the different receiver characteristics?
2. How to examine and compare the sensitivity and performance of two different receivers under the impact of atmospheric turbulence and its fading vector?
Chapter 2 - Theoretical Background of Optical Receivers

2.1 Intensity Modulation Direct Detection

In commercial FSO systems, IM/DD using APD receiver is used since the implementation of the direct detection receiver is easy and it can be designed easily [1]. The function of the IM/DD receiver is to convert the optical signal into electrical signal. Intensity modulation direct detection receiver can transmit the signal in the form of intensity or power [4]. Intensity modulation carries the information signal as intensity or power and not by its frequency or phase [4]. In a direct detection optical receiver, photodiode is act as a detector and it converts the input optical light wave electric field into an electrical current at the receiver side [5]. Intensity modulation technique using APD receiver is used to modulate the source signal and then it transmits from the modulator as a laser signal to the ground station [1]. The laser signal is transmitted from aircraft through the atmospheric fading channel to the optical ground station, see Figure 2.1

![Figure 2.1 Transmission of laser optical signal from aircraft to optical ground station](image-url)
2.2 Responsivity of the APD

BER of the direct detection system has been derived with its K-distributed atmospheric turbulence channel model in [6] and outage probability was mentioned in [7]. In [6] and [7] the FSO system was done using the PIN photo detector. Since PIN photodiodes are too insensitive for an IM/DD system only use of APD makes sense for higher performance systems. Hence an Avalanche Photodiode (APD) provides higher sensitivity than a normal photodiode. An avalanche photodiode is shown in Figure 2.2. The use of APDs instead of PIN Photo detectors will result in improved sensitivity in the IM/DD receiver. In a direct detection receiver, responsivity of the avalanche photodiode is comparatively higher than the responsivity of the PIN photodiodes [2]. Characteristics of avalanche photodiode devices and performance of APD-based receivers have been studied extensively in the literatures [8], [9].

![Figure 2.2 An avalanche photodiode](image)

2.3 Distributions for Atmospheric Fading Condition

Performance of the APD receiver with taking the shot and thermal noise into account is presented in [2]. In the mentioned paper the log normal distribution is used for the week-to-moderate and gamma-gamma distribution is used for the moderate-to-strong atmospheric condition. The Gaussian distributed fading vector is also one of the simplest way to use it
CHAPTER 2. THEORETICAL BACKGROUND OF OPTICAL RECEIVERS

numerically and it is simple to calculate the performance of the receiver. There are two types of photodiodes used; the PIN photodiode which is shown schematically in Figure 2.3 and the avalanche photodiode. Both operated according to the same basic principles. PIN photodiode converts photons to electron hole pairs with efficiency $\eta$.

$$S = \sqrt{P_x} e^{j\omega t}$$

**Figure 2.3 Schematic representation**

2.4 Heterodyne Detection

The function of the coherent receiver is to convert the optical signal to an electrical signal by means of heterodyne detection [10]. The coherent optical receiver is shown in Figure 2.4. Evaluating the performance of the coherent optical receiver under atmospheric turbulence condition is challenging. Received signal is to be added with the mixer i.e. local oscillator, has attained the various types of noise by optical to electrical conversion process and atmospheric turbulence [11].

**Figure 2.4 Coherent Optical receiver**
CHAPTER 2. THEORETICAL BACKGROUND OF OPTICAL RECEIVERS

Receiver front end consists of collecting lens and PIN photo detector and the output signal from the receiver is used to conclude the performance of the receiver by solving the bit error rate expression [12]. Atmospheric channel model is Gaussian rather than the log normal distribution after the turbulence takes place [12]. In the above mentioned paper Gaussian distribution is observed after the atmospheric turbulence takes place.

2.5 Noise Component in the Optical Receiver

In the optical receiver the received optical signal is converted into electrical signal with the help of photo detector, and during the conversion takes places the different kind of noise will affect the received signal which is in the form of electrical signal. Different kind of noise present in the optical receivers are shot noise and thermal noise and these are modeled as an additive white Gaussian noise [1].

2.5.1 Shot Noise

Primary photocurrent \( I_p \) is directly proportional to the optical power level is given by [5]

\[
I_p = RP_R
\]  

(2.1)

where \( R \) is the responsivity and \( P_R \) is the received optical power.

The shot noise is because of the random fluctuation of the electric current of the number of photons respectively. The shot noise was first investigated by Schottky in 1918. In time domain the instantaneous current \( I(t) \) of the photo detector can be written as [5]

\[
i(t) = I_p + i_s(t)
\]  

(2.2)

where \( i_s(t) \) is the current fluctuation due to the shot noise and \( I_p \) is the primary photocurrent.

The noise variance of the shot noise becomes [13]

\[
\sigma_s^2 = \langle i_s^2(t) \rangle = 2qI_p\Delta f
\]  

(2.3)

where \( q \) is the electronic charge and \( \Delta f \) is the effective noise bandwidth of the receiver.

The effective noise bandwidth is given as [5]

\[
\Delta f = 2qI_p \int_0^{\infty} |H(f)|^2 df
\]  

(2.4)

where \( H(f) \) is the transfer function of the filter.

Since dark current \( I_d \) also has a shot noise the total variable of the shot noise is given by [5]

\[
\sigma_s^2 = 2q(I_p + I_d)\Delta f.
\]  

(2.5)
2.5.2 Thermal Noise

The thermal noise is because of the random thermal motion of the electrons in a conductor [5]. The thermal is added in the load resistor connected to the photo diode. This noise component has been first studied by Johnson and Nyquist and is therefore known as Johnson-Nyquist noise [13].

Taking the current fluctuation through thermal background noise by modifying the equation 2.2

\[ i(t) = I_p + i_s(t) + I_T(t) \]  \hspace{1cm} (2.6)

where \( I_p \) is the primary photocurrent, \( i_s(t) \) is the current fluctuation due to the shot noise and \( I_T(t) \) is the current fluctuation induced by thermal noise.

The variance of the thermal noise is given by [13], [14]

\[ \sigma_T^2 = \left( \frac{Ak_BT}{R_L} \right) \Delta f F_n \]  \hspace{1cm} (2.7)

Where

- \( k_B \) is the Boltzmann constant
- \( T \) is the receiver temperature
- \( R_L \) is the APD’s load resistor
- \( F_n \) is the amplifier noise and
- \( \Delta f \) is the effective noise bandwidth
Chapter 3 - IM/DD system using APD

3.1 Sensitivity and performance of the direct detection receiver

Sensitivity of the IM/DD system is attained by calculating the SNR of the receiver. Different kinds of noise which are presents in the IM/DD system are divided with the signal power to calculate the SNR of the receiver. Performance of the system is identified by calculating the bit error rate of the received signal. The received signal has attained various types of noise by optical to electrical conversion processes and atmospheric turbulences which result in data loss occurs. Data loss of the received signal is calculated by using the conditional probability distribution function. This is one of finest method to identify the data loss occurs in the received signal.

3.2 IM/DD System using APD

PIN photodiodes are too insensitive for an IM/DD system, so only use of APD makes sense for higher performance systems. SNR of the APD receiver is higher than the PIN photodiode for same level optical power [5]. An electron with enough kinetic energy can knock a bound electron out of its bound state and promote it to a state in the conduction band, creating an electron-hole pair and it is called as impact ionization [15]. In Figure 3.1 the receiver front end consists of optical preamplifier and avalanche photodiode. At the receiver, an optical signal is converted to an electrical signal by using photo detector [1].

![Figure 3.1 Front end of an Optical IM/DD system](image)

Impact ionization will give the photocurrent gain if the multiplication factor M gives the high electric field [16]. The total shot noise for the APD is given by [17]
CHAPTER 3. IM/DD SYSTEM USING APD

\[
\sigma_s^2 = 2qMF_A(RP_R + I_d)\Delta f
\]  
(3.1)

where \( F_A \) is the excess noise factor of APD, \( q \) is the electronic charge, \( M \) is the multiplication factor, \( R \) is the responsivity, \( P_R \) is the received optical power, \( I_d \) is the dark current and \( \Delta f \) is the effective noise bandwidth of the receiver.

In [18], the excess noise factor model is calculated. \( F_A \) is a function of carrier ionization ratio \( k_A \).

Excess noise factor is given by

\[
F_A = k_A M + (1 - k_A) \left( 2 - \frac{1}{M} \right)
\]  
(3.2)

where \( k_A \) is the ratio of hole-electron ionization rate to that of electrons, \( M \) is the multiplication factor.

SNR of the IM/DD receiver is not influenced by the shot noise and the thermal noise dominance will give the better result, since the multiplication gain will not play a role here [5].

\[
SNR = \frac{i_p^2}{\sigma^2} = \frac{(MRP_R)^2}{2qM^2F_A(RP_R + I_d)\Delta f + \left( \frac{4k_BT}{R_L} \right)\Delta f F_N}
\]  
(3.3)

By substituting the various hole-electron ionization rate from 0.01 to 0.5 in the excess noise factor to check the effect of the AMF gain. Figure 3.2 shows the plot between excess noise factors with the function of AMF.
3.3 Background Noise in the IM/DD system

Additional source noise had to be taken into account to calculate the SNR of an IM/DD system. Optical receiver that enhances the background radiation is just because of the dependency of the field of view and bandwidth. Since the background noise present because of the field of view of the receiver has mixed up with the incoming source signal. The SNR of the above calculated equation is to be added up with the background noise. The variance of the background noise is [19]

\[ \sigma_{BG}^2 = 2R^2 S_{\lambda, BG} (2P_R + \Delta f_{op} S_{\lambda, BG}) \Delta f \]  

(3.4)

where

- \( S_{\lambda, BG} \) is the optical power spectral density of the background noise,
- \( \Delta f_{op} \) is the optical filter bandwidth limiting the background noise,
- \( R \) is the responsivity,
- \( P_R \) is the received optical power and \( \Delta f \) is the effective noise bandwidth of the receiver.
Attaining the large incident power will influence the shot noise to be high and it makes the performance of the receiver to be worse. APD shot noise is influenced by the background shot noise and the background APD shot noise becomes as [5]

\[
\sigma_{BG}^2 = 2qM^2F_A(RP_R + I_d + R\Delta f_{op}S_{\lambda,BG})\Delta f
\]

SNR of the IM/DD system including the background noise is given by

\[
SNR = \frac{I_p^2}{\sigma^2} = \frac{(MRP_R)^2}{2qM^2F_A(RP_R + I_d)(\Delta f + (\frac{4kPR}{R_L})\Delta f + M^2F_A2R^2S_{\lambda,BG}(2P_R + \Delta f_{op}S_{\lambda,BG})\Delta f)}
\]  \hspace{1cm} (3.5)

SNR equation in equation (3.5) is compared with the noise and signal power of the system to calculate the SNR value of the IM/DD receiver. Comparison will be done with the received power of -40dBm. This is shown in Chapter 5 - Figure 5.3 and Sensitivity of the IM/DD receiver is calculated by plotting the PDF curve with the function of SNR value with the same fading vector and with received power of -40dBm. This is shown in the Chapter 5 - Figure 5.9. The values of the system parameters and constants are given in Table 1. These values are used to numerically calculate the SNR value. SNR of the IM/DD system including the background noise derived in the equation (3.5) is calculated numerically and implemented in the Figure 5.1, Figure 5.2, Figure 5.3 and Figure 5.4 using the system parameters and constants given in the Table 1.

**Table 1: IM/DD System input parameter values to numerically analyze the SNR**

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>( \lambda = 1550 \times 10^{-9} )</td>
<td>m</td>
</tr>
<tr>
<td>Load Register</td>
<td>( R_L = 0.15 \times 10^4 ) Ohm</td>
<td></td>
</tr>
<tr>
<td>Circuit Temperature</td>
<td>( T = 273.15 + 24 ) K</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>( \delta f = 1.25 \times 10^9 ) Hz</td>
<td></td>
</tr>
<tr>
<td>Dark Current</td>
<td>( I_d = 3.3 \times 10^{-9} )</td>
<td>-</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>( e = 0.94 )</td>
<td>-</td>
</tr>
<tr>
<td>Ionization coefficients</td>
<td>( k_A = 0.02 )</td>
<td>-</td>
</tr>
<tr>
<td>Radiance</td>
<td>( \text{Rad} = 3 \times 10 ) mW/m^2srnm</td>
<td>mW: 1550nm</td>
</tr>
<tr>
<td>Bandwidth of optical filter</td>
<td>( \lambda_{\text{filter}} = 10 \times 10^{-9} )</td>
<td>M</td>
</tr>
<tr>
<td>Receiver Telescope Diameter</td>
<td>( D_{Rx} = 0.5 ) m</td>
<td></td>
</tr>
<tr>
<td>Field of View</td>
<td>( FOV = 200 \times 10^{-6} ) ( \mu \text{rad} )</td>
<td></td>
</tr>
</tbody>
</table>

11
3.4 Optimum APD Gain

The optimum value depends on a large number of receiver parameters such as dark current, the responsivity R and the ionization coefficient ratio \( k_A \), however it is independent of receiver bandwidth. Figure 3.3 shows the variations of \( M_{opt} \) with \( P_{in} \) for several values of \( k_A \). The results are numerically implemented using the values of system parameters and constants that are given in Table 2. The optimum APD Gain is quite sensitive to the ionization coefficient ratio \( k_A \).

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>( \text{lambda} = 1550 \times 10^{-9} )</td>
<td>M</td>
</tr>
<tr>
<td>Load Resister</td>
<td>( R_L = 0.15 \times 10^4 )</td>
<td>Ohm</td>
</tr>
<tr>
<td>Noise Figure of Amplifier</td>
<td>( F_n = 5 )</td>
<td></td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>( \text{etha} = 0.94 )</td>
<td></td>
</tr>
<tr>
<td>Electron charge</td>
<td>( q = 0.1602 \times 10^{18} )</td>
<td>C</td>
</tr>
<tr>
<td>Planks Constant</td>
<td>( h = 0.662 \times 10^{-33} )</td>
<td>Js</td>
</tr>
<tr>
<td>Speed of light</td>
<td>( c = 299792458 )</td>
<td>m/s</td>
</tr>
<tr>
<td>Optical frequency</td>
<td>( f = \frac{c}{\text{lambda}} )</td>
<td>Hz</td>
</tr>
<tr>
<td>Responsivity</td>
<td>( R = \left( \frac{\text{etha} \times q}{h \times f} \right) )</td>
<td>A/W</td>
</tr>
</tbody>
</table>
CHAPTER 3. IM/DD SYSTEM USING APD

Figure 3.3 Optimum APD gain with a function of received optical power

Figure 3.3 is calculated by applying the various electron ionization value $k_A$ in the excess noise factor $F_A$.

3.5 Gaussian Noise

Noises present in the channel may be neither Gaussian nor independent of the signal. The statistics of the signal should be known to make a decision error by calculating its probability. Exact statistics should be evaluated numerically, since the APD output statistics are complicated and different compromises have to be made to calculate accurately. The easiest way of calculating the bit error rate is called Gaussian approximation. In [20] it explains that the Gaussian approximation differs from the exact statistics is no more than $0.5\text{db}$ when used to estimate the signal strength required to obtain a bit rate of $10^{-9}$.

3.6 Analyze the BER of IM/DD system

In this section the performance of the IM/DD receiver is discussed by deriving the BER calculation, and the numerical implementation values are also tabled with the exact measured parameters of this receiver. Though the SNR calculation is to identify the performance of the
receiver this is not sufficient enough. Considering the performance of the IM/DD system with
the BER calculation should be accurate enough.
For an IM/DD system the received optical current is expressed as [5]
\[ I_p = MRP_R \]  (3.6)
where
\[ M \] is the average APD gain
\[ R \] is the responsivity and
\[ P_R \] is the received power
Gaussian approximation and exact statistics are the two ways to calculate the output signal.
Exact statistics should be evaluated numerically, even though it provide a good result the APD
output statistics are complicated and different compromises have to be made to calculate the
signal accurately. Difference between Gaussian approximation and exact statistics is not more
than 0.5db to calculate the output signal [20]. Since in Figure 5.9 the PDF of the input signal is
considered as Gaussian distribution vector with the noises consider in the mark state is shot
noise, thermal noise, shot noise due to the dark current and background noise and noise consider
in the space state is only the shot and thermal noise [21], [22]. Expression of the mark state is
\[
P_m = \frac{1}{\sigma_{ms}\sqrt{2\pi}} \exp \left[ -\frac{(I_{p})^2}{2\sigma_{ms}^2} \right] \text{ for the mark state} \quad (3.7)
\]
In IM/DD receiver, we express the variance of the noise in the receiver as \( \sigma_{ms}^2 \) when the signal is
in the mark state, this can be calculated as
\[
\sigma_{ms}^2 = \sigma_s^2 + \sigma_{BG}^2 + \sigma_{BGs}^2 + \sigma_T^2
\]
where \( \sigma_s^2 \) is the total shot noise, \( \sigma_{BG}^2 \) is the variance of background noise, \( \sigma_{BGs}^2 \) is the background
shot noise and \( \sigma_T^2 \) is the thermal noise.
Expression of the space state is
\[
P_s = \frac{1}{\sigma_{ss}\sqrt{2\pi}} \exp \left[ -\frac{(I_{o})^2}{2\sigma_{ss}^2} \right] \text{ for the space state} \quad (3.8)
\]
In IM/DD receiver, we express the variance of the noise in the receiver as \( \sigma_{ss}^2 \) when the signal is
in the space state, this can be calculated as
\[
\sigma_{ss}^2 = \sigma_s^2 + \sigma_T^2
\]
where \( \sigma_s^2 \) is the total shot noise and \( \sigma_T^2 \) is the thermal noise.
CHAPTER 3. IM/DD SYSTEM USING APD

In [17] the complementary error function is given by
\[
\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-t^2) \, dt = 1 - \text{erf}(x) \quad (3.9)
\]

Since it is easy to calculate the BER numerically using the function erfc in Matlab. We can write the mark state and space state as
\[
\mathcal{M} = \frac{1}{2} \left\{ \text{erfc} \left( \frac{I_p-I_{TH}}{\sigma_{ms} \sqrt{2}} \right) + \text{erfc} \left( \frac{I_{TH}}{\sigma_{ss} \sqrt{2}} \right) \right\} \quad (3.10)
\]

where \( \frac{I_p-I_{TH}}{\sigma_{ms} \sqrt{2}} = \frac{I_{TH}}{\sigma_{ss} \sqrt{2}} = Q \) (Qualification factor), since the above equation depends on threshold value \( I_{TH} \). We optimized it and the BER of IM/DD can be written as
\[
\text{BER}_{IM/DD} = \frac{1}{4} \left[ \text{erfc} \left( \frac{I_p}{\sqrt{2} (\sigma_{ms} + \sigma_{ss})} \right) \right] \quad (3.11)
\]

For estimating the performance of the IM/DD system we can use qualification factor as [31].
\[
Q = \frac{I_p}{\sigma_{ms} + \sigma_{ss}} \quad (3.12)
\]

The BER of IM/DD systems is then written as
\[
\text{BER}_{IM/DD(Q)} = \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \quad (3.13)
\]
Chapter 4 - Heterodyne Detection

4.1 Sensitivity and Performance of the Coherent (Heterodyne) Receiver

Robustness of the coherent receiver is identified by deriving the sensitivity and performance of the receiver. Sensitivity of the coherent receiver is calculated by deriving the signal-to-noise ratio with the system parameters. We can attain the high sensitivity for the coherent receiver by increasing the received optical power, but getting the high sensitivity with the low power is good. Then the robustness of the system will be very high.

For coherent detection system the received optical current $I_p$ is expresses as

$$I_p = 2R^2P_{lo}P_R$$

(4.1)

where $R$ is the responsivity, $P_{lo}$ is the local oscillator power and $P_R$ is the received optical power.

4.2 Signal to Noise Ratio

The total noise variance of the heterodyne receiver is by adding the shot noise and thermal noise and it becomes

$$\sigma^2 = 2q(I_p + I_d)\Delta f + \left(\frac{4k_BT}{R_L}\right)\Delta f F_n$$

(4.2)

where $q$ is the electronic charge, $I_p$ is the primary photocurrent, $I_d$ is the dark current, $\Delta f$ is the effective noise bandwidth of the receiver, $k_B$ is the Boltzmann constant, $T$ is the receiver temperature, $R_L$ is the APD’s load resistor, $F_n$ is the amplifier noise and $\Delta f$ is the effective noise bandwidth.

The ratio of the signal power (Eq. 4.1) and noise power (Eq. 4.2) is then written as [5]

$$SNR_{heterodyne} = \frac{2R^2P_{lo}P_R}{2q(I_p + I_d)\Delta f + \left(\frac{4k_BT}{R_L}\right)\Delta f F_n}$$

(4.3)

Shot Noise that are present in the IM/DD system will differ in the Coherent receiver. The shot noise dominates with the local oscillator power and will get the mixed up noise with the local oscillator power influence in it. So the dominant local oscillator power variable is replaced in equation (4.3) and the SNR becomes

$$SNR_{heterodyne} = \frac{2R^2P_{lo}P_R}{2q(P_{lo}R + I_d)\Delta f + \left(\frac{4k_BT}{R_L}\right)\Delta f F_n}$$

(4.4)
CHAPTER 4. HETERODYNE DETECTION

By neglecting the influence of the shot noise due to the dark current will made a difference in performance of the SNR [5].

\[
SNR_{\text{heterodyne}} = \frac{RP_R}{2q}\Delta f = \frac{\eta P_R}{2h\nu\Delta f}
\]  

(4.5)

where \(\eta\) is the quantum efficiency, \(h\) is the planck’s constant and \(\nu\) is the frequency.

Sensitivity of the heterodyne detection receiver is calculate by plotting the PDF curve with the function of SNR value with the same fading vector and with received power of -40dBm. This is shown in the Figure 5.9

4.3 Background Noise in the Heterodyne System

Additional source of noise has to be taken into account to calculate the SNR of a heterodyne system. Optical receiver that enhances the background radiation is just because of the dependency of the field of view and bandwidth. Since the background noise present because of the field of view of the receiver has mixed up with the incoming source signal the SNR of the above calculated equation is to be added up with the background noise [19]. The variance of the background noise is given by

\[
s_{BG}^2 = 2R^2 s_{\lambda, BG}(2P_R + \Delta f_{op}S_{\lambda, BG})\Delta f
\]  

(4.6)

where

\(s_{\lambda, BG}\) is the optical power spectral density of the background noise, \(\Delta f_{op}\) is the optical filter bandwidth limiting the background noise, \(R\) is the responsivity, \(P_R\) is the received optical power and \(\Delta f\) is the effective noise bandwidth of the receiver.

SNR of the heterodyne system is influenced by the background noise and it is given by [5]

\[
SNR_{\text{heterodyne}} = \frac{2R^2P_R P_{LO}}{2q(P_{LO}R + I_d + R\Delta f_{op}S_{\lambda, BG})\Delta f + \left(\frac{4\nu P_R^2}{RL}\right)\Delta f_P + 2R^2s_{\lambda, BG}(2P_R + \Delta f_{op}S_{\lambda, BG})\Delta f}
\]  

(4.7)

The SNR equation we attained here is compared with the noise and signal power of the system to calculate the SNR value of the coherent receiver. Comparison will be done with the received power of -40dBm. This is shown in Figure 5.7. The values of the system parameters and constants are given in Table 3, and these values are used to numerically calculate the SNR value.

SNR of the coherent detection system influenced by the background noise derived in the equation (4.7) is calculated numerically and implemented in the Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8 using the system parameters and constants given in the Table 3.
Table 3: Coherent System input parameter values to numerically analyze the SNR

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$\lambda = 1064 \times 10^{-9}$</td>
<td>m</td>
</tr>
<tr>
<td>Load Register</td>
<td>$R_L = 0.15 \times 10^4$</td>
<td>Ohm</td>
</tr>
<tr>
<td>Circuit Temperature</td>
<td>$T = 273.15 + 24$</td>
<td>K</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$\Delta f = 1.25 \times 10^9$</td>
<td>Hz</td>
</tr>
<tr>
<td>Dark Current</td>
<td>$I_d = 30 \times 10^{-9}$</td>
<td>-</td>
</tr>
<tr>
<td>Noise Figure Amplifier</td>
<td>$F_n = 5$</td>
<td>-</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>$\eta = 0.94$</td>
<td>-</td>
</tr>
<tr>
<td>Ionization coefficients</td>
<td>$k_A = 0.02$</td>
<td>-</td>
</tr>
<tr>
<td>Radiance</td>
<td>$Rad = 3e1$</td>
<td>$\frac{mW}{m^2 \times m^2}$, 1mW: 1550nm</td>
</tr>
<tr>
<td>Bandwidth of optical filter</td>
<td>$D\lambda = 10 \times 10^{-9}$</td>
<td>m</td>
</tr>
<tr>
<td>Receiver Telescope Diameter</td>
<td>$D_{Rx} = 0.5$</td>
<td>m</td>
</tr>
<tr>
<td>Field of View</td>
<td>$FOV = 100 \times 10^{-6}$</td>
<td>$\mu$ rad</td>
</tr>
</tbody>
</table>

4.4 Analyze the BER of the Coherent System

Performance of the coherent receiver is done by calculating the BER method and the numerical values have been tabulated under this topic. Using the system parameter values in Matlab to compare the coherent detection system with IM/DD to compare the performance among the receivers.

For and coherent detection system the received optical current is expresses as [5]

$$I_p = 2R^2 P_{Lo} P_R$$  \hspace{1cm} (4.8)

where

- $R$ is the responsivity
- $P_R$ is the received power and
- $P_{Lo}$ is the local oscillator power
The noise in the receiver is considered to be the narrow receiver bandwidth of the coherent receiver, and it is given by [21], [24]

\[ n(t) = x(t) \cos \omega_{IF} t - y(t) \sin \omega_{IF} t \]  

(4.9)

where \( \omega_{IF} \) is the angular frequency, \( x(t) \) and \( y(t) \) are the input signal.

Noise components in the coherent system are controlled by a shot noise due to the influence of the local oscillator. Since the noise components are controlled by a local oscillator the noise becomes equal in the mark state and space state. Therefore we assume [21]

\[ \sigma_{m,s,c}^2 = \sigma_{s,s,c}^2 = \sigma_c^2 \]  

(4.10)

In coherent receiver, we express the noise in the receiver as \( \sigma_{m,s,c}^2 \) when the signal is in the mark state and \( \sigma_{s,s,c}^2 \) when the receiver is in the space state.

Variance of \( x(t) \) and \( y(t) \) are

\[ x(t)^2 = y(t)^2 = \sigma_c^2 \]

In coherent detection light wave system noises considered in the PDF of an input signals are the shot noise and thermal noise. Various kind of noise that is influenced while transmitting the signal are the background noise. In coherent receiver, we express the variance of the noise in the receiver as \( \sigma_{m,s,c}^2 \) when the signal is in the mark state, this can be calculated as [24]

\[ \sigma_{m,s,c}^2 = \sigma_{BG}^2 + \sigma_{sh}^2 + \sigma_T^2 \]  

(4.11)

where \( \sigma_{BG}^2 \) is the background noise, \( \sigma_{sh}^2 \) is the total shot noise and \( \sigma_T^2 \) is the thermal noise.

In coherent receiver, we express the variance of the noise in the receiver as \( \sigma_{s,s,c}^2 \) when the signal is in the space state, this can be calculated as [24]

\[ \sigma_{s,s,c}^2 = \sigma_{sh}^2 + \sigma_T^2 \]  

(4.12)

where \( \sigma_{sh}^2 \) is the total shot noise and \( \sigma_T^2 \) is the thermal noise.

The SNR of the signal \( SNR_{heterodyne} \) can be expressed in terms of \( I_{s,c} \) and \( \sigma_c \) as

\[ SNR_{heterodyne} = \frac{I_{s,c}^2}{2 \sigma_c^2} \]  

(4.13)

The BER can be obtained as [5]

\[ BER = \frac{1}{2} \text{erfc} \left( \frac{I_{s,c}}{\sigma_c \sqrt{2}} \right) \]  

(4.14)

\[ BER_{heterodyne} = \frac{1}{2} \text{erfc} \sqrt{SNR_{heterodyne}} \]  

(4.15)
CHAPTER 4. HETERODYNE DETECTION

BER equation we got here is used to find out the performance of the Coherent receiver. BER is plotted with the SNR value to check the performance of the receiver. BER for $10^{-9}$ is plotted in the graph which is shown in Figure 5.11. Monte Carlo method was handled to target a very low BER curve [6].

4.5 Monte Carlo method

Monte Carlo method is particularly used where analytical methods are tough to apply [25]. This method is a broad class of computational algorithm that relies on repeated random number sampling to obtain numerical results [25]. This method is used to attain a very low BER. The BER of the Receivers can be checked to the minimum extend using this method. The low BER can targets from $10^{-6}$ to $10^{-9}$ [6]. Monte Carlo simulation is one of the finest alternative analytical tools for less time consuming [25].
Chapter 5 - Experimental Result

5.1 Comparison of Noise and Signal Power of IM/DD System

The noise signals which are present in the optical IM/DD receiver are derived in the chapter 3. There is no need of including all the background noises, we consider some of the noise signals during the comparison of noise and signal power as well as the SNR of the IM/DD receiver. Figure 5.1 shows the performance of the SNR curve and the noise signals dominant in the receiver. In IM/DD receiver the SNR value is not stable, we can see it clearly in the Figure 5.1. The SNR curve is gradually decreasing once it reaches to the maximum value of 30.4dB which is also shown in the Figure 5.1. SNR value of the IM/DD receiver should be calculated at the steady state of the SNR curve. In Figure 5.1 we got the high SNR value at the steady state of the SNR curve but the AMF value become very less for the received optical power of -30dBm. By taking the AMF value into account the received optical power of -30dBm is not considered to evaluate the performance of the IM/DD receiver.

Figure 5.1 SNR, Signal and Noise Power of IM/DD receiver with received power of -30dBm

Figure 5.2 shows the received optical power of -50dBm. SNR value of the IM/DD receiver should be marked or calculated at the steady state of the SNR curve. In Figure 5.2 steady state of
the SNR curve is attained at the maximum value of an AMF. The value of an AMF for the received optical power of -50dBm becomes high to evaluate the performance of the IM/DD receiver but the SNR value of the IM/DD system for the received optical power of -50dBm become very less. High sensitivity and performance of the receiver can be achieved only with the high SNR value. SNR value of the IM/DD receiver is attained for the received optical power of -50dBm is only 6.543dB which is in the Figure 5.2 and this SNR value will reduce the sensitivity of the receiver. Even though the AMF value is high to evaluate the performance of the IM/DD receiver by taking the SNR value into account the received optical power of -50dBm is also not considered.

![SNR, Signal and Noise Power of APD receiver with P_r = -50.00 dBm](image)

**Figure 5.2 SNR, Signal and Noise Power of IM/DD receiver with received power of -50dBm**

### 5.2 Comparison of Signal and Noise using Received Power of -40dBm for IM/DD

Comparison of noise signals and signal power with the received optical power of -40dBm in Figure 5.3 gives the perfect solution to get a considerable AMF and SNR values. SNR value should be marked at the steady state of the SNR curve. In Figure 5.3 steady state of the SNR
curve is attained for the AMF value of 52.5. SNR value attained at the steady state of the SNR curve for the received power of -40dBm is 19.11dB which is in Figure 5.3. Compare to the Figure 5.1 and Figure 5.2 in Figure 5.3 for the received optical power of -40dBm the SNR value and the AMF value is perfect and by taking this both values into account we considered the received optical power of -40dBm to evaluate the performance of the IM/DD receiver. Considered the SNR and APD gain values in Figure 5.3 to calculate the PDF and to compare the sensitivity of the coherent and IM/DD receivers.

Figure 5.3 SNR, Signal and Noise Power of IM/DD receiver with received power of -40dBm

Figure 5.4 is plotted using the AMF value of 52.5 which is obtained in the Figure 5.3 for the received optical power of -40dBm. Figure 5.4 shows the performance of the SNR curve of an APD receiver using an AMF value of 52.5. In Figure 5.4 noise signals, signal power and the SNR curve of an APD receiver are plotted against the received optical power for the achieved AMF value of 52.5 in Figure 5.3. SNR value of an APD receiver is marked in the Figure 5.4 at the received optical power of -40dBm gives the exact SNR value which is attained in the Figure 5.3. Figure 5.4 is plotted to check the SNR value of the IM/DD receiver for the given AMF value
CHAPTER 5. EXPERIMENTAL RESULT

of 52.5 and it gives the exact SNR value is 19.11dB in the Figure 5.4 which is already achieved in the Figure 5.3.

5.3 Comparison of noise and signal power of Coherent Detection system

Dependency of the received optical power and noise presented in the receiver with the received optical power of -30dBm and -50dbm are shown in the Figure 5.5 and Figure 5.6. The system parameter values and the noise which are present in the coherent receivers are explained in the Chapter 4 - . In Figure 5.5, Figure 5.6 and Figure 5.7 graph includes all types of noise signals presents in the coherent detection system. Figure 5.5 will briefly shows the attained value of all the noise signals, signal power and the SNR for the received optical power of -30dBm. Figure 5.5 also shows the performance of the SNR curve and the noise signals dominant in the receiver. In coherent receiver the SNR value is stable, we can see it clearly in the Figure 5.5 the SNR curve is maintaining the stable value once it reaches the maximum SNR value of the
curve. SNR value of the coherent receiver should be calculated at the maximum value of the SNR curve, since the system is stable the SNR value is constant once the SNR curve reaches the maximum value in the coherent receiver. In Figure 5.5 the SNR value of the coherent receiver is 36.1 dB.

![Figure 5.5 SNR, Signal and Noise Power of Coherent receiver with received power of -30dBm](image)

Figure 5.5 SNR, Signal and Noise Power of Coherent receiver with received power of -30dBm

SNR value of the coherent receiver should be marked at the maximum value of the SNR curve. Figure 5.6 shows the SNR value of the coherent receiver for the received optical power of -50dBm is 16.1 dB. Even though the received optical power of -30dBm in Figure 5.5, and -50dBm in Figure 5.6 gives the good SNR values to evaluate the performance of the coherent receiver. We consider only the received optical power of -40dBm in Figure 5.7 to evaluate the performance of the coherent receiver, because Figure 5.3 is calculated with the received power of -40dBm gives the perfect solution to get the considerable AMF and SNR values for the IM/DD receiver. In order to evaluate and to compare the performance of Coherent and IM/DD receivers we need to consider the same received optical power in both the receivers.

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CHAPTER 5. EXPERIMENTAL RESULT

5.4 Comparison of Signal and Noise using Received Optical Power of -40dBm for Coherent Detection system

SNR values of the Coherent detection system are calculated with the system parameter values which are mentioned in the Chapter 4. System parameter values of the Coherent detection system are not same as that of the IM/DD system but the fading vector and the received optical power are same. Figure 5.7 shows clearly, that the SNR value of the coherent detection system is higher than the IM/DD system for the received optical power of -40dBm. SNR value attained at the maximum value of the SNR curve is 26.1 dB which is in the figure 5.7. Considered this SNR value of the Coherent detection system obtained in the Figure 5.7 to plot the PDF curve in comparison with the SNR value of the IM/DD system attained in the Figure 5.3 to check the
sensitivity of both the receivers and to check the performance of both the receivers. In Figure 5.9 the PDF curve is plotted.

**Figure 5.7 SNR, Signal and Noise Power of Coherent receiver with received power of -40dBm**

SNR value attained in the Figure 5.8 is 26.1dB. In Figure 5.8 noise signals, signal power and the SNR curve of the coherent receiver are plotted against the received optical power. SNR value of the coherent receiver is marked in the Figure 5.8 at the received optical power of -40dBm gives the exact SNR value which is attained in the Figure 5.7. Figure 5.8 is plotted to check the performance of the coherent receiver and it gives the exact SNR value of 26.1dB which is already achieved in the Figure 5.7.
CHAPTER 5. EXPERIMENTAL RESULT

![Graph showing SNR, Signal and Noise Power of Coherent receiver](image)

**Figure 5.8 SNR, Signal and Noise Power of Coherent receiver**

### 5.5 SNR comparison of IM/DD and coherent detection receiver

Probability of IM/DD system is broader than the coherent detection system. Though the same fading vector is used in both receivers. The PDF curve of the coherent receiver system is sharp and looks good under the atmospheric condition. Probability of attaining the SNR of the coherent receiver is more sensitive than the IM/DD system. The optical mean received power used in the system is -40dBm. SNR value of the coherent receiver which is attained from the Figure 5.7 is mentioned here in blue color and the SNR value of IM/DD system which is attained from the Figure 5.3 is mentioned is black color. The SNR value of the coherent receiver is 26.1 for the given optical power of -40dBm and the SNR value of the IM/DD receiver is 19.11 for the same optical power used in the Coherent receiver. Sensitivity of both the receiver is clearly seen from the Figure 5.9, it proves that the Sensitivity of the coherent receiver is more than the sensitivity of the IM/DD receiver in terms of fading vector.
CHAPTER 5. EXPERIMENTAL RESULT

Figure 5.9 Sensitivity Comparison of Coherent and IM/DD receiver curve with the received power of -40dBm

5.6 Integration of PDF curve

Cumulative distribution function is calculated by integrating the probability density function of both the coherent and IM/DD systems with the same parameter values used in the system models. Figure 5.10 shows that both the curve attains here reach the value one.

Figure 5.10 Cumulative distribution function
CHAPTER 5. EXPERIMENTAL RESULT

5.7 Bit Error Rate analysis of the IM/DD system

BER of the IM/DD is done with considering the additive white Gaussian distribution vector with the noises present in both systems. The Bit rate of $10^{-9}$ is aimed, which is the very low BER targets to achieve a very less data loss. To achieve the target Monte Carlo method was used to extend the curve to the minimum possible point of $10^{-9}$.

![Additive white gaussian simulation](image)

Figure 5.11 BER performance comparison of Coherent and IM/DD receiver

Figure 5.11 shows that the BER curve of the Coherent detection system becomes sharper at some point than comparing to the BER of IM/DD system. Figure 5.11 shows that the performance of the coherent detection system is better than the IM/DD system.
Chapter 6 - Conclusion

In this project, I have compared the sensitivity and performance of the coherent detection and IM/DD receivers. The probability was analytically derived by taking into account the atmospheric turbulence and receiver noise, which includes the shot noise and thermal noise and it is modeled as additive white Gaussian noise. The atmospheric turbulence is modeled by Gaussian distribution.

Unlike the previous works, I have derived the signal-to-noise ratio of the heterodyne detection and IM/DD receivers to analyze the sensitivity of both the receivers. In Figure 5.9, it is clearly shown that the sensitivity of the Coherent receiver provides a better PDF curve than the sensitivity of the IM/DD receiver.

Solving the bit error rate simulation of coherent and IM/DD receivers is the main target of the project. Bit error rate simulation to achieve the low BER value like $10^{-9}$ was extremely time-consuming and not possible for regular method to achieve till $10^{-9}$, so the alternative method is handled in the project to achieve the very low bit error rate target was the Monte-Carlo simulation.

Bit error rate performance of both the receivers using Monte-Carlo simulation is obtained in Figure 5.11. In the Monte Carlo simulation graph it is clearly shown that improvement of the BER curve in the coherent detection system provides a better performance than the BER curve in the IM/DD system.

In comparison to the coherent and incoherent receivers with the same fading vector under atmospheric turbulence, sensitivity of the coherent receiver gives the best result and it is proven in the sensitivity comparison Figure 5.9 and the performance of the coherent receiver gives the best result at the target BER rate of $10^{-9}$ and it is proven in the BER performance comparison Figure 5.11.
References


