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Analyzation study of FSO Telecommunication System: Effect of Fog, Rain, and Snow at 1550 nm Wavelength

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Abstract:

The main goal of these papers is to analyze the Free space optical system with the weather condition of Ankara, the capital city of turkey. Governmental meteorological data support the analysis of this study of wireless communication systems; where it provides real measurement values. The advantages of the FSO system are the simplicity and the cost of installation in comparison with fiber optic systems that use light amplified as a source for transmission. This system is used in short-range applications, which are between buildings in cities or between skyscrapers, and sometimes between ships, as well as very complex military situations. The laser generally is used as a signal transmitter because it has a special optical advantage that allows it to travel long distances. Telecommunications engineers normally prefer to use semiconductor lasers because of their special properties and their cost-effectiveness. The obstacles that face the FSO system are different weather conditions such as rain, fog, air molecules, and snow. This study will investigate the FSO using a semiconductor laser according to the weather conditions of Ankara and the distance traveled taking into account a good high-quality data transmission.

***Keywords* — Meteorological data, BER, Semiconductor Lasers, short-range application.**

I. INTRODUCTION

The FSO system is a wireless communication system that uses the laser beam as a transmitter. The transmission between buildings using the (LOS) line of site technique. Data transmitted must be converted to bits 0's and 1's then sent as optical pulses and the receiver will be a photo-detector which means detecting the light and converting it to information. The disadvantage of the system is that the system will be affected by bad weather [1].

FSO system used the light amplified by a laser to send the data from far away within the air as a medium. The unguided media does not require any physical medium to send the light which is as known as an electromagnetic signal. FSO works in free space which means air, provides an optical bandwidth connection, and propagates in outer space, vacuum, or something similar, to wirelessly transmit data for telecommunication and computer networking [1].

Nowadays, the FSO data rate is up to 2.5 Gbps of data video and voice communications through the air, allowing optical connectivity to be the media without using fibreoptic cable [2]. The rule of thumb in using FSO is the short-range applications and sure it will be hard to depend on this system for the long term at high or mid-range applications. Increasing the distance means a high telescope in terms of the receiver. FSO components are mainly like any telecommunication system consisting of three stages: a transmitter to send the optical signal through the media which is the atmosphere that follows Beer-Lambert's law, channel (free space) where it's contained (cloud, rain, smoke, gases, temperature variations, fog, and aerosol) and receiver to received signal[1].

The next table will give an overview of the difference between RF systems and FSO systems. The most important point that describes the advantages of FSO systems are summarized in the table.

Table 1 RF systems vs FSO systems[3].

Technology	RF	FSO
Available Spectrum	300 GHz	100s THz
Licensing	Licensed	Unlicensed
Terminal Foot-prints	Bulk	Small
Energy Consumption	Tens of [W]	Tens of [mW]
Data Rates	Mbits / Gbits	Tera bits
Configuration	LOS/ NLoS	LOS
Latency	Moderate	Low
Noise sources	Interference with other users	Background ambient light
Safety	Subject to EMF radiations	Eye and skin safe
Security	Susceptible to Eavesdropping	Secure
Sensitivity to Pointing Errors	Low	High

Because it's important to define the laser used and how will be controlled output. This concept will be studied further and then analyzed. Control of the output of laser transmitted is important because the signal will be affected by the weather condition and the weather condition will add attenuations to the signal. Therefore, it's important to study the effect of changing power related to weather which is related to the received signal. Furthermore, the models of weather conditions that describe the main weather condition (Fog, Snow, and Rain) have been generated.

Controlling the power of the transmitter is done by controlling the power out of the laser that passes throw the air which means also controlling components of the semiconductor laser as the transmitter that is used. Friis equation describes the received signal by the transmitted signal and the channel component. Based on the Friis equation the weather condition will be concluded. The semiconductor laser is used widely in telecommunication and especially in FSO systems because it can maintain the wavelength needed in transmission with eye safety international standards and emits a very tiny area of light in one direction that reduces the hazard to humans and animals[4].

Also, a Semiconductor laser is compact in size, rugged, and has low-cost maintenance. Also, the cost of the laser itself is cheap in comparison with other lasers therefore it will affect the cost of the system overall. Therefore, it's good to use the semiconductor laser in the FSO system. The main laser construction that affects the output power is the mirrors inside it. However, the laser mirror is mainly involved in the generated formula [5], [6]. After a careful review of the equation and accurate calculation of the resulting quantities, suitable values for mirrors and the rest of the components were found to give the proper results that need. Therefore, these results were confirmed throughout the study.

II. LASER MODEL

Laser stand for light amplification stimulated emission radiation[7]. It radiates the amplification light that generates on the active medium by mirrors. Generally, all types of lasers, are working similar concepts but the difference between each other of them is the type of active medium, pumper types, and also mirrors (shape and numbers). The coherence of light out of laser is the main visual realized deference from normal light. The laser also gives a narrow beam which means less diffraction of light. This happens because of the stimulated emission concept used in a laser instead of spontaneous emission used in light[7].

Based on a study of a photon lifetime and the carrier lifetime with threshold current that needs the reflectivity of the mirrors, one of the mirrors will be 99% and the second one will be 55% the next formulas give steps to generate the laser output equation they will be as follow [7]:

$$Ith = \frac{q * v * Nth}{Te} \quad 1$$

$$Tp = \frac{1}{Vg(\sigma m + \sigma i)} \quad 2$$

$$\sigma m = \frac{1}{L} \ln\left(\frac{1}{R1 * R2}\right) \quad 3$$

$$\mathrm{th} = Ntr + \frac{1}{\Gamma * Vg * g * Tp} \quad 4$$

$$Te = \frac{1}{A + BNth + CNth} \quad 5$$

$$PoutB = (\frac{\sigma m}{\sigma m + \sigma i})\frac{hv}{q}(I - Ith) \quad 6$$

The last equation number 6 is describing the internal power of the laser and it will be generated at the time of stimulated emission start[7].

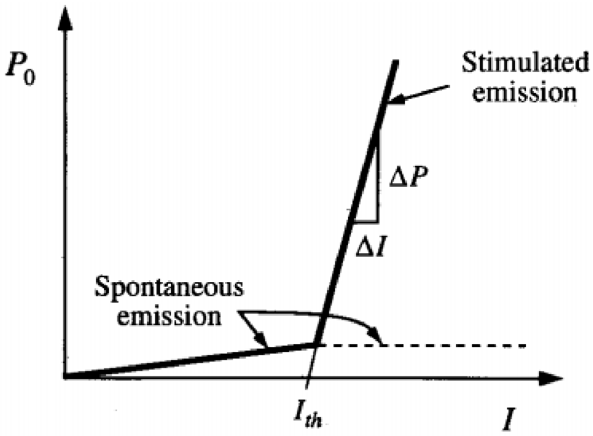

Figure 1 The change of power related to current[7].

The output laser formula based on the equations 18a, 18b and 18c [8] will be as follow:

$$Pout = PoutB(\frac{((1 - R2^2) * R1)}{((1 - R2^2) * R1) + ((1 - R1^2) * R2)}) \quad 7$$

III. Signal Model

To generate the signal model of the received signal the Friis equation will be used and regenerated based on a new type of attenuation. The Beer-Lambert law, known also as Beer's law relates the attenuation of light to the properties of the things passed in front of the light traveling [9]. Friis equation is generated based on beer's law.

Also, for the weather condition, the fog will be described as the Kim model and the rain formula with snow will be generated based on ITU standards. The transmitter and receiver telescope gain will be for 4 types of apertures that will give a good of it and the results in the next section. The noise model will be calculated and after that, at the end of the section, all the components will conclude on the received power formula.

The received signal[2]:

$$Ps = Pout * Gr * Gt * Ta * TF * LFS \quad 8$$

The Pout as described before represents the output power where Gr and Gt are the transmitter and receiver telescope gain. Then Ta is the atmospheric transmission coefficient and TF is an optical filter transmissivity and LFS is the free-space loss.

Gt and Gr [2]:

$$Gr = \pi * \frac{Dr}{\lambda} \quad 9$$

$$Gt = \left(2 * \pi * \frac{Wt}{\lambda}\right)^2 \quad 10$$

Where Dr is receiver aperture and Wt is transmitter aperture. The LFS calculation:

$$LFS = \left(\frac{4 * \pi * L}{\lambda}\right)^2 \quad 11$$

Where L is the distance between the transmitter and receiver.

The rest is Ta which is the important factor that will help calculate the atmospheric condition that needs to be involved in the equation of received power. This attenuation will be replaced by the weather condition model.

IV. Weather Condition Model

Because the fog is the main problem for the FSO system which mean the visibility is not as normal so whenever the vision is high mean the fog is less and vice versa. Therefore, it's clear that the fog is related to visibility. There are many models for fog but the most used one is the Kim model.

Kim model is assuming that there is permitter q that can range of visibility from 0.5 to 50 km. and it's concluded on calculation[10].

$$q = \begin{cases} 1.6 & \text{if V} > 50\text{ km} \\ 1.3 & \text{if } 6\text{ km} < \text{V} < 50\text{ km} \\ 0.16V + 0.34 & \text{if } 1\text{ km} < \text{V} < 6\text{ km} \\ V - 0.5 & \text{if } 0.5\text{ km} < \text{V} < 1\text{ km} \\ 0 & \text{if V} < 0.5\text{ km} \end{cases}$$

Figure 2. q Factor with Kim model.

Then the Kim model formula[11] will be:

$$\sigma = \frac{3.912}{V}\left[\frac{\lambda}{550}\right] \quad 12$$

$$Ta(fog) = e^{\sigma L} \quad 13$$

$sigma\ is$ the Kim attenuation coefficient and Ta(fog) represent attenuation that comes out from fog[12].

Rain & Snow Attenuation:

Generally, rain can be approximated by the next relation:

$$Ta(rain) = aR^b \quad 14$$

Where a = 1.076 and b= 0.067 are constant with the frequency 1550 nm. And R(mm/h) is will rate of rain in weather conditions [11].

The attenuation due to the snow as a function of snowfall rate will be calculated as follow:

$$Ta(snow) = aS^b \quad 15$$

Where a and b are constant can be calculated based on the next table for the S (snowfall rate)[11].

	a	b
Wet snow	0.0001023λ+3.7855466	0.72
Dry snow	0.0000542λ+5.4958776	1.38

Then the total Ta of the weather condition will be:

$$Ta = Ta(snow) * Ta(rain) * Ta(fog) \quad 16$$

TF will be equal to 0.5 it's constant of received telescope[2].

V. Noise Model

Many important noise factors should be concluded to calculate the signal-to-noise ratio. Even though the noise that is considered a dominant in the FSO systems is thermal and the background noise but there is much noise that should be calculated[2].

The background noise equation can be calculated by the next equation:

$$PBG = Ar * FOV * \Delta\lambda * TF * Rrad \quad 17$$

This is the noise that arises on the detection of inserted photons that generated by the environment involved in background light such as the sun. where Ar is the receiver's effective primary area and FOV is the receiver's field of view and Rrad is reflected solar radiance.

Then to calculate the variance of the PBG noise is calculated by the next formula:

$$\sigma BG = 2q * R * PBG * B \quad 18$$

Thermal noise is also important to calculate therefore the variance formula[2]:

$$\sigma th = \frac{4 * K * Te * F * B}{RL} \quad 19$$

RL: load resistance
F: Noise figure.
Te: Equivalent temperature.
B: Electronic bandwidth.
K: Boltzmann's constant

Relative Intensity Noise (RIN) is defined as the instability of the laser source power which affects the (SNR) signal-to-noise ratio[2]. detector's current variance caused by RIN and can be calculated:

$$\sigma(RIN) = RIN * \left((R)Ps\right)^2 * B \quad 20$$

Where
R: detector responsivity.
Ps: received power.

Dark current is the current through a photoconductive or a photoelectric cell whenever an electromotive force or power is applied in the absence of light in an FSO system[8]. Therefore, it should be included in the calculation. The variance of the detector current results from the photodiode dark current can be expressed by

$$\sigma DC = 2 * q * IDC * B \qquad 21$$

Shot noise one of detecting noise referred to as quantum noise or photon noise generally comes out from the fluctuations in the number of photons detected at the receiver photodiode[8]. The variance of shot noise in the detector can be calculated by the following formula:

$$\sigma sh = 2 * q * R * Ps * B \qquad 22$$

VI. BIT ERROR RATE AND SIGNAL-TO-NOISE RATIO

This ratio is defined as a single numeric value that is described by the beneficial value of power related to the noise on the received power in decibels (dB). A ratio can be zero, a negative number, or a positive number which clarifies that the ratio over zero (dB) means that the signal level is greater than the noise level. The higher this ratio indicates that the better the signal quality has been received [13].

To calculate the signal-to-noise ratio it's important to calculate the total power received and the total internal noise that is applied to the receiver[14]. The next equation will be the calculation of SNR[2]

$$SNR = \frac{R * Ps}{\sigma 0 + \sigma 1} \qquad 23$$

$$\sigma 0 = \sigma DC + \sigma sh + \sigma BG \qquad 24$$

$$\sigma 1 = \sigma DC + \sigma sh + \sigma BG + \sigma(RIN) + \sigma th \qquad 25$$

Finally, the BER calculation. It will help to know if the system is efficient or not. By using the Erfc probability Gaussian Distribution function the Bit error rate will be related to the SNR as the following formula:

$$BER = \frac{1}{2} erfc(\frac{1}{2\sqrt{2}} * \sqrt{SNR}) \qquad 26$$

Bit Error Rate (BER) is one of the telecommunication measurements that is used to check the percentage of the signals received incorrectly. That means the more incorrect bits indicate a worsening of impact on signal quality. A result of 10^9 is considered an acceptable BER, and 10^{13} is a more appropriate BER to help with data transmission[15].

VII. RESULT AND DISCUSSION

To send data in wireless communication it's important to have good enough power in the received area. The weather effect the passing distance of these types of FSO systems with the weather condition. Analyzing the data of received power will cover three types of weather Fog, Snow, and Rain. The equations and results have been studied graphically and compared with the international laboratory results, and also compared with the results of another similar research.

A large group of cases was studied and the cases were merged and then conclusions were drawn from them and several hypotheses were developed to extract the largest amount of information and to make the research suitable for everyone who wants to implement this system.

Then we made a strenuous study of those drawings and deduced from them a large set of results and they were linked to the solar system of Ankara city. The results are based on real numbers obtained from Turkish meteorology to give a greater chance for the results to be realistic.

the cases that have been studied are:

- Received power with fog.
- Received power with snow.
- Received power with Rain.
- Received power with Rain and snow.
- Received power with Rain with fog.
- Received power with fog and snow.
- Received power with fog, rain, and snow.

These cases also have been studied for 4 types of apertures of transmitter and 4 types of receiver apertures. Also, for all these cases 4 types of current injection have been concluded.

After that, both SNR and BER have to be calculated for all these cases and graphed. And the results of BER cases will be a combination of fog, rain, and snow system for one case of injection current with one case transmitter aperture and receiver aperture.

The total cases that have been studied are 448 cases and in the last of this section will be some of the samples of them.

The results that have been approved are the following:

1) Based on four values of transmitter aperture that have been chosen for this study, it can be noticed that the higher transmission aperture means a higher of the distance of pass means the system can go longer.
2) On the other side also the higher the receiver aperture the higher distance can pass throw the different weather conditions.
3) The change of current injection will affect also the distance passed; the higher the injection currents the higher of distance.
4) Taking the worst accepted situation of the weather condition within the past 5 years in Ankara city (2017~2021), the FSO system can travel for 1 km with a good BER. That means this type of system can be a good application for short-distance systems.
5) The average distance that can be said the weather condition is on acceptable values for fog, rain, and snow, the FSO system can travel for 28 km with accepted BER.
6) In the case that fog is on the lowest values and no rain and no snow falling (normally in summer) the system can travel for 60 km with a good BER.

To increase the distance that the FSO system can travel with the different weather conditions there are many solutions suggested:

- Insert controller for injection current that injected to laser transmission.
- Use a transceiver that will be on between the transmitter and receiver.
- Use a higher aperture on the laser transmission or PD (photodiode) that received the signal.
- Use auto rechargeable transceiver drone between transmitter and receiver.

VIII. SAMPLE OF THE RESULTS.

The next graphs are the samples of the graphs that have been generated and analyzed. We have used 4 levels of injection current with all the changes that applied in the received power. It’s important to put in mind that these data have been applied to most of the weather conditions.

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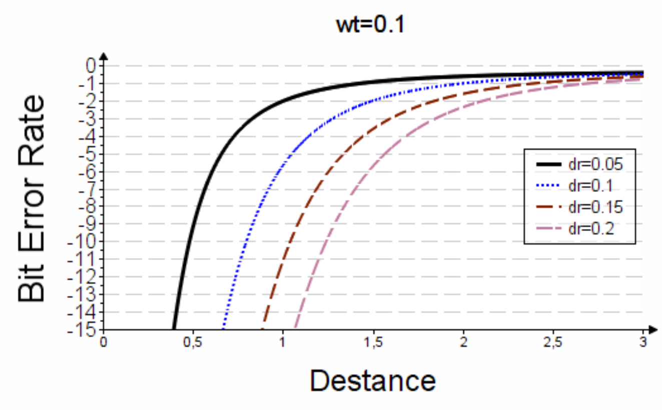

Figure 3 Worst case for high rain. With rain =24 mm/h snow 0.8 mm/h and visibility =20K and wt= 0.1

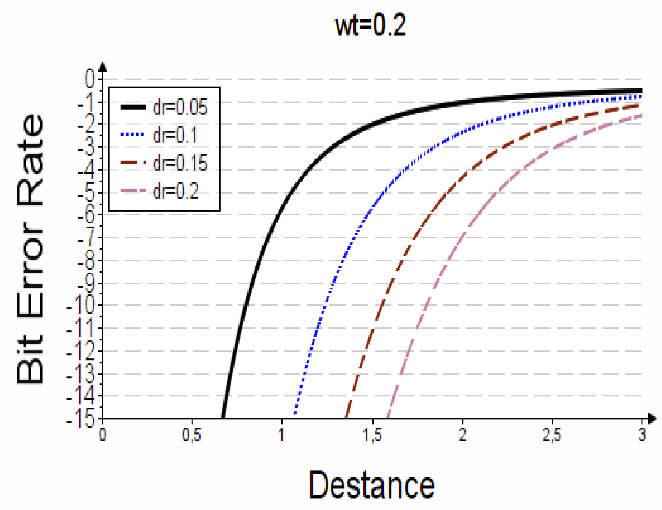

Figure 4 Worst case for high rain. With rain =24 mm/h snow 0.8 mm/h and visibility =20K and wt= 0.2

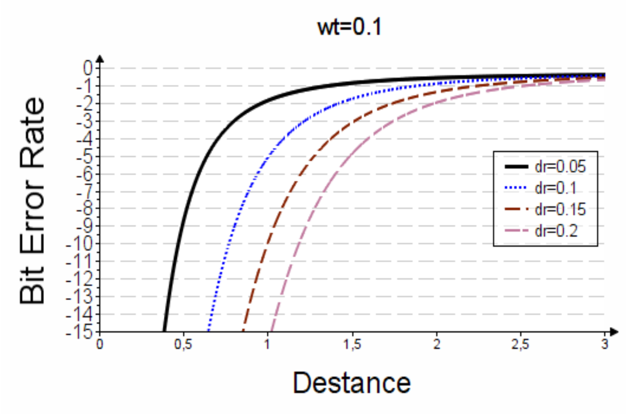

Figure 3 Accepted case for rain =17.8 mm/h snow 1 mm/d and visibility =15K and wt= 0.1.

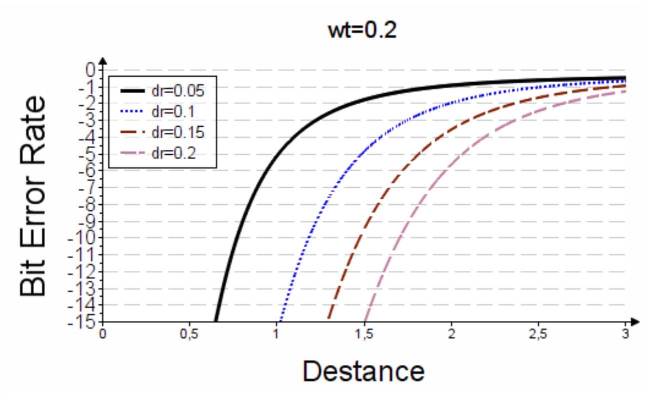

Figure 6 Accepted case for rain =17.8 mm/h snow 1 mm/d and visibility =18K and wt= 0.2

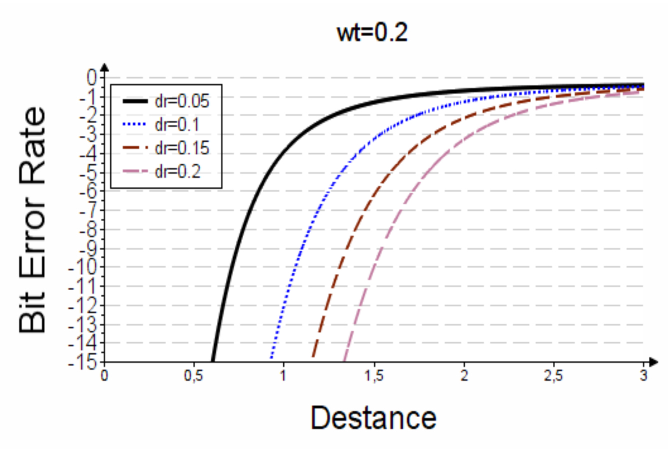

Figure 7 Accepted case for rain =17.8 mm/h snow 1 mm/d and visibility =21K and wt= 0.2

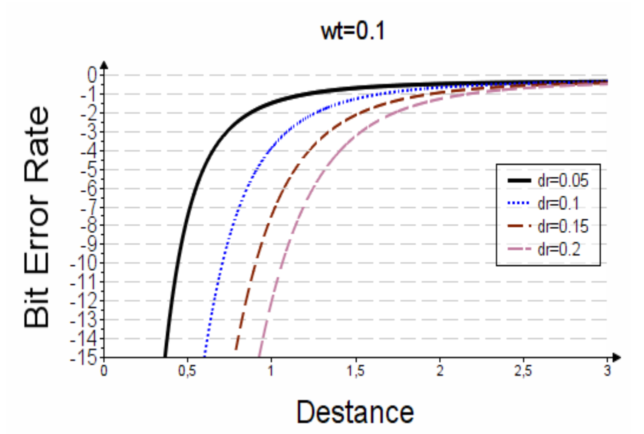

Figure 4 Accepted case for rain =17.8 mm/h snow 1 mm/h and visibility =22K and wt= 0.1

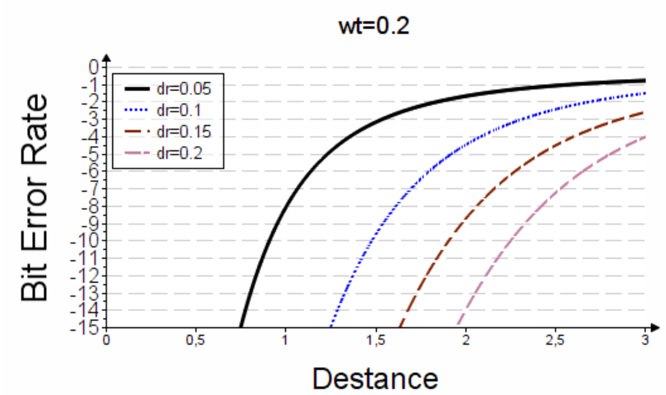

Figure 9 Good case for rain =5.6 mm/h snow 0.3 mm/h and visibility =21K and wt= 0.2

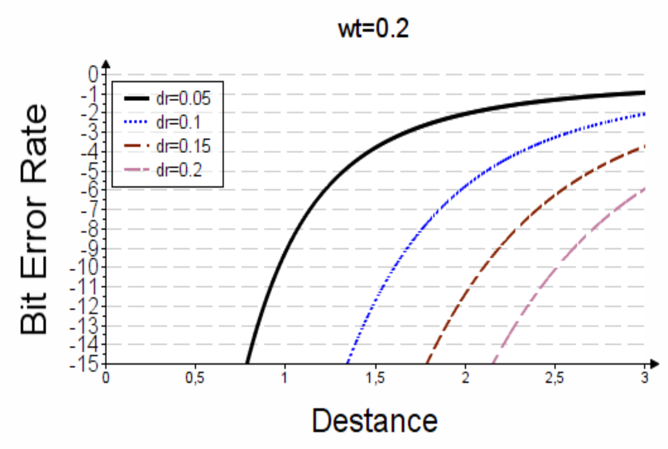

Figure 10 One of good case for rain =0.2 mm/h snow 0.1 mm/d and visibility =20K and wt= 0.2

Now it's important to mention the values that fixed on these papers.

Table 2 Fixed values.

Quantity	Symbol	Value				Unit
Threshold current	*Ith*	0.19				mA
Receiver aperture	dr	0.05	0.1	0.15	0.2	mm
Transmitter aperture	wt	0.05	0.1	0.15	0.2	mm
Optical filter transmissivity	TF	0.5				
Earth object blackbody temperature	T	300				K
Load resistance	RL	100				Ω
Circuit noise figure	F	4				
Equivalent temperature	Te	290				K

IX. CONCLUSIONS

We analyzed the FSO system on the weather condition of Ankara. This analysis will help the designer of the system and scientists to improve more in wireless systems in general and in turkey especially. The analysis of this system takes into consideration that there are many laser types to work in weather conditions. Therefore, the laser construction kept in general values to help in future work on improving the special type for every condition.

The contribution between changing the values of receiver aperture and transmitter aperture with changing of the injection current help too much to understand the overall changes in the action happening on received power. The result that comes up is logically accepted in a telecommunication system for the short-range application. The simplicity and cost of systems like the FSO system attract in researchers to improve the system for cities and connection between people. The analyzed that done of the system performance was done by determining its SNR and BER with consideration of dominant noise sources. If this system should apply eye safety should take into consideration.

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