Calculations of Signal to Noise Ratio (SNR) for Free Space Optical Communication Systems

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Abstract

In this paper, we calculate and measure the SNR theoretically and experimental for digital full duplex optical communication systems for different ranges in free space, the system consists of transmitter and receiver in each side. The semiconductor laser (pointer) was used as a carrier wave in free space with the specification is 5mW power and 650nm wavelength. The type of optical detector was used a PIN with area $1mm^2$ and responsively 0.4A/W for this wavelength. The results show a high quality optical communication system for different range from (300-1300)m with different bit rat (60-140)kbit/sec is achieved with best values of the signal to noise ratio (SNR).

Introduction

Optical Signal to Noise Ratio (SNR) is the measure of the ratio of signal power to noise power in an optical channel. For a typical optical communication system for which the SNR is relevant, the signal consists usually of nearly monochromatic modulated light superimposed on a background comprised of (mostly unmodulated) optical power distributed over a broad wavelength range - a range including the signal wavelength [1].

This noise arises typically in optical amplification and it is better thought of as a power density rather than a total power. When the optical signal is carried by an optical transmission system that includes optical amplifiers. The detection of the signal is typically affected by attenuation and dispersion. With the use of amplifiers, there is the additional impairment because of noise seen in the receiver due to the presence of ASE (Amplified Spontaneous Emission) noise. In practice, the use of an amplifier will help improve the signal because the increase in the signal amplitude will help overcome noise generated in the receiver's front end. However, the optical background (noise) that accompanies the desired optical signal will be amplified along with the signal; consequently, the SNR will tend to degrade as it passes through the transmission system. The optical noise near the signal wavelength can impair the receiver's ability to properly decode the signal because of optical interference between the optical signal and optical noise. This impairment can be a bigger contributor to the BER than the power fluctuations in the optical noise, especially when an optical filter centered on the signal wavelength is placed ahead of the receiver.

This "free space" technique requires only a clear line-of-sight path between the transmitter and the distant receiver to form an information link. The availability of a coherent, monochromatic optical communication which, due to the very high frequency of the carrier (10^{14} Hz), would allow a very large amount of information to be transmitted. Figure (1) shows a block schematic of a typical digital optical communication system,

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initially the input digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of semiconductor laser with the encoded digital signal. The photodetector is followed by a preamplifier to provide gain. Finally, the obtained signal is decoded to give the original digital information [2].

The full duplex optical communication system consists of a transceiver unit which consist mainly of the transmitter unit and receiver unit, The signal could be sent and received in a free space between two which are terminal 1 and 2 [3].

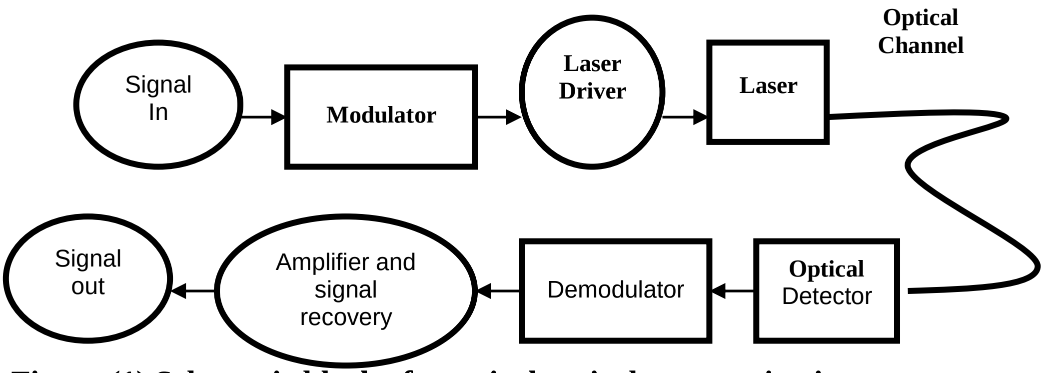


Figure (1) Schematic block of a typical optical communication system

The system of pulses modulated should be driven to the laser source by using driver circuit. Circuit applies the needed current to the laser in order to control of the output power of the laser. While the output pulse was detected using optical detector must be amplified using high speed operational amplifier. The amplifier was designed to get a gain equal to 10k by selection the feedback resistance equal to 10kΩ and input resistance equal to 1kΩ.

Measurement and Calculations

The signal to noise ratio of the system could be calculated as follows [4]:-

$S/N = 20 \log_{10} (i_s / i_n)$ in dB (using voltage or current ratio)............. **(1)**

Where the symbol S represents the optical signal power and the symbol N is the optical noise power, i_n generated current noise in optical detector and i_s generated signal current.

The two main sources of noise in optical detector without internal gain are thermal noise (Johnson noise) and dark current.

The Johnson noise voltage is expressed in terms of the mean square voltage developed across a load resistance of R_L (in Ohms) at a temperature T (in Kelvin) in a frequency (Δ f) [5, 6] :-

Where k is Botzmann's constant,

$\boldsymbol{k = 1.38066 \times 10^{-23}}$ **J/K**

$$i_{th} = \sqrt{\frac{4\,k\,T\,\Delta f}{R_L}} \quad \ldots(2)$$

Therefore the total current noise is:-

$$\mathbf{i_n = i_{th} + i_d} \quad \ldots (3)$$

Where i_d is the dark current.

The system work at the room temperature **(i.e. T=300 K)**, $\mathbf{R_L=22k\Omega}$ is load resistor, and the signal bandwidth **Δf=(60,80,100,120,140)kb/s,** while i_d=4 nA by substitute these values in equation(2) and (3), the results of the thermal noise current $\mathbf{i_{th}}$ and the total current noise $\mathbf{i_n}$ are listed in the table(1) :

Table 1: The thermal noise current and the total current noise as a function of bit rate

Δf(kb/s)	i_{th} (nA)	i_n (nA)
60	21.2	25.2
80	24.5	28.5
100	27.4	31.4
120	30.0	34
140	32.45	36.45

The amount of the generated current in the photodiode (i_s) depends on the incident optical power on the photodiode P_r (μW), and the responsivity R_λ =0.4 (A/W) [7].

$$i_s = P_r \times R_\lambda \quad \ldots\ldots\ldots.. \ (4)$$

The total power of the received signal through the earth's atmosphere can be calculated by:

$$P_{receiver} = P_{transmit} \times \frac{A_{receiver}}{(Div * Range)^2} \times \exp(-\mu * Range) \ldots (5)$$

$$A_{receiver} = \pi \times (D2 / 4) \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The theoretical calculation of the received optical signal power of the system can be calculated, the maximum output power $P_{transmitted}$ of the optical transmitter for laser diode pointer is 5mW and laser beam divergence 0.6 mrad, $A_{receiver}$ of the optical receiver 0.0028cm^2, the atmospheric transmittance T_a of laser wavelength 650nm is about 62% and the range R= [300,500,650,700,1000,1300].
by substitute these values in equation (4) and (5) we obtain the table (2) below:

Table 2: The received power (theoretical and experimental) as a function of range

Range (m)	P_r (theoretical) μW	i_s(theoretical) μA	P_r (experimental) μW	i_s(experimental) μA
300	267	106.8	148	59.2
500	96	38.4	78	31.2
650	57	22.8	37	14.8
700	49	19.6	26	10.4
1000	24	9.6	1.2	2.4
1300	14	5.6	0.9	0.36

When substitute the values in the table (2) in equation (1) we obtain:-

At bit rate 60 kb/s

Table 3: The theoretical and experimental values of the S/N at bit rate 60 kb/s

i_s μA (theoretical)	S/N (dB)(theoretical)	i_s μA (experimental)	S/N (dB)(experimental)
106.8	72.54	59.2	67.41
38.4	63.65	31.2	61.85
22.8	59.13	14.8	55.37
19.6	57.81	10.4	52.31
9.6	51.61	2.4	39.5
5.6	46.93	0.36	23.09

At bit rate 80 kb/s

Table 4: The theoretical and experimental values of the S/N at bit rate 80 kb/s

i_s(theoretical) μA	S/N dB(theoretical)	i_s(experimental) μA	S/N dB(experimental)
106.8	71.47	59.2	66.34
38.4	62.58	31.2	60.78
22.8	58.06	14.8	54.3
19.6	56.74	10.4	51.24
9.6	50.54	2.4	38.5
5.6	38.86	0.36	22

At bit rate 100 kb/s

Table 5: The theoretical and experimental values of the S/N at bit rate 100 kb/s

i_s(theoretical) μA	S/N dB(theoretical)	i_s(experimental) μA	S/N dB(experimental)
106.8	70.63	59.2	65.5
38.4	61.74	31.2	59.94
22.8	57.22	14.8	53.46
19.6	55.9	10.4	50.4
9.6	49.7	2.4	37.66
5.6	45.02	0.36	21.18

At bit rate 120 kb/s

Table 6: The theoretical and experimental values of the S/N at bit rate 120 kb/s

i_s(theoretical) μA	S/N dB(theoretical)	i_s(experimental) μA	S/N dB(experimental)
106.8	69.94	59.2	64.81
38.4	61.05	31.2	59.25
22.8	56.53	14.8	52.77
19.6	55.24	10.4	49.71
9.6	49	2.4	36.97
5.6	44.33	0.36	20.49

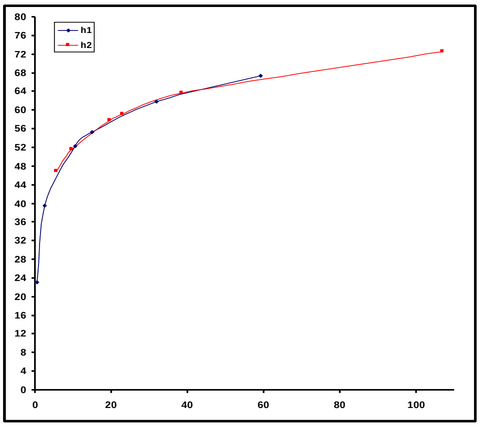
At bit rate 140 kb/s

Table 7: The theoretical and experimental values of the S/N at bit rate 140 kb/s

i_s(theoretical) μA	S/N dB(theoretical)	i_s(experimental) μA	S/N dB(experimental)
106.8	69.33	59.2	64.2
38.4	60.45	31.2	58.65
22.8	55.92	14.8	52.17
19.6	54.6	10.4	49.1
9.6	48.41	2.4	36.37
5.6	43.73	0.36	19.89

The variation of the S/N with the power received which is represented by the generated signal current in optical detector are shown in figures 1,2,3,4,5 at different b.t rats.

S/N (dB)

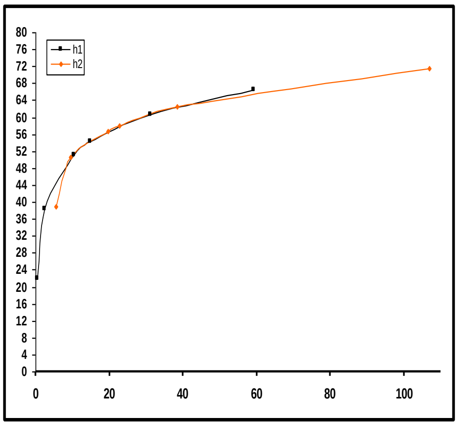


$i_s(\mu A)$

Figure (1)

The SNR as a function of signal current at i_n=25.2 (nA) & frequency carrier 60KHz

S/N (dB)

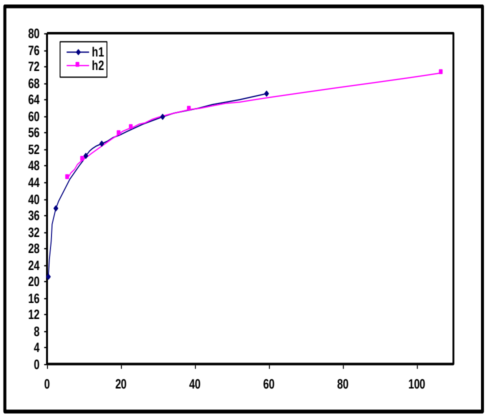


$i_s(\mu A)$

Figure (2)

The SNR as a function of signal current at in=28.5 (nA) & frequency carrier 80KHz

S/N (dB)

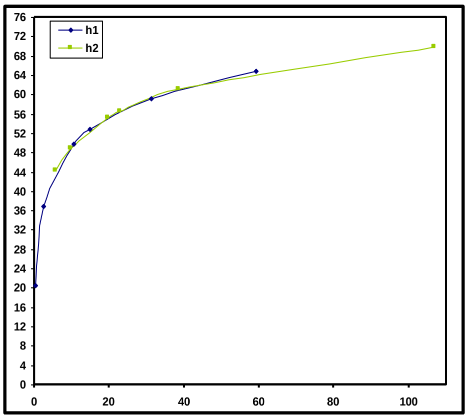


$i_s(\mu A)$

Figure (3)

The SNR as a function of signal current at in=31.4 (nA) & frequency carrier 100KHz

S/N (dB)

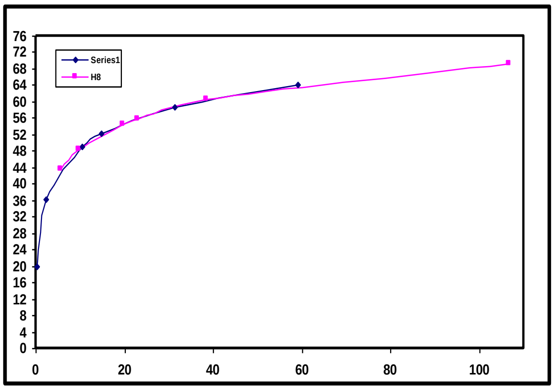


$i_s(\mu A)$

Figure (4)

The SNR as a function of signal current atin=34 (nA) & frequency carrier 120KHz

S/N (dB)



$i_s(\mu A)$

Figure (5)

The SNR as a function of signal current at in=36.4 (nA) & frequency carrier 140KHz

It can be seen from above figures when the range is increase the generated signal current decreases due to decreasing of the received power which is led to decreases of the S/N.

While the relationship between the signals current (i_s) generated in optical detector, noise current and S/N is shown as in figure (6).

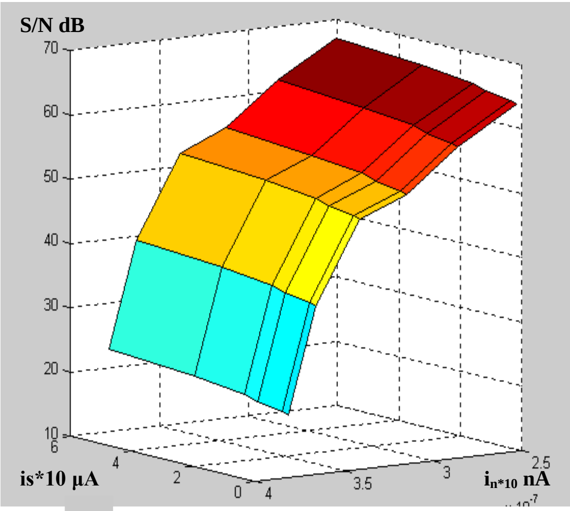


Figure (6)
The relationship between the S/N, i_s& i_n

From an above figure the increasing of the signal current generated in optical detector due to the incident of the power received on the optical detector leads to increasing of the SNR quality of the system because of dependence on the power received which is a directly proportional with the signal current generated in optical detector. While the SNR is decreasing with increasing of the noise current generated due to attenuation in optical detector.

It can be observed from the figure (6) that S/N is directly proportional with i_s and in the same time it is inversely proportional with i_n.

The above figure shows the optimized value of the i_s in the range between (40-50)μA and frequency carrier range between (90-110)kb/s. This would allow a wide selected frequency range in this region to obtain a good quality signal and less noise.

Conclusions

- Since the system is thermal noise limited, increasing the load resistance leads to reduce the thermal noise and then increases SNR, in addition to decreasing the minimum detectable power and increasing the system power margin.
- We can see the optimum value of SNR achivied at the carrier frequency is (100kb/s), because of this value of carrier frequency gives as minimum value of the thermal noise.
- By increasing the bandwidth Δf of transmitted signal of the system, the thermal noise will increase in accordance to with the equation (2), which leads to decreases in SNR.

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حساب نسبة ألاشارة الى الضوضاء لمنظومة أتصال ضوئية في الفراغ

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الخلاصة:

تم في هدا البحث حساب وقياس نسبة الاشارة الى الضوضاء (SNR) نظريا وعمليا لمسافات مختلفة وبمعدل نقل بيانات مختلفة بعد ان تم حساب القدرة المستلمة لكل مسافة لمنظومة أتصالات ضوئية رقمية متعاكسة الاتجاه لمسافات مختلفة في الجو, تتكون المنظومة من مرسلة ومستلمة في كل جانب تم أستخدام الليزر كوسط ناقل وخصائص الليزر المستخدم في هذه المنظومة هو نوع ليزر أشباه الموصلات مرئي (pointer) بقدرة مقدارها 5mW وبطول موجي 650nm والكاشف الضوئي المستخدم نوع فوتوني سليكوني PIN وبمساحة $1mm^2$ وبأستجابية 0.4A/W لهذا الطول الموجي. أثبتت النتائج ان منظومة الاتصالات الضوئية المصممة ذات كفاءة عالية لعدة نقل بيانات (60-140)kbit/sec ولعدة مسافات مختلفة (300-1300)m من خلال الحصول على أفضل قيم لنسبة الاشارة الى الضوضاء.