Maximizing the Area Spanned by the Optical SNR of the 5G Using Digital Modulators and Filters

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Abstract: *High security data link channels having more immunity against channel noise is the need of the century. Free Space Optical communication (FSO) is the modern technology which kick-starts it's application in inter satellite communication, underwater communication and mobile communication to the next level of data transmission by means of complete utilisation of the allocated frequency spectrum. In Europe and Asian countries, 5G optical communication will going to expand its usage to nearly 50% in upcoming years and so bandwidth and power efficiency has to be enhanced as much as possible since the consumption rate of the users is increasing exponentially. But increasing the distance increases the attenuation in case of severe atmospheric weather condition. In this paper, 5G data rate of 50Gbps is ensured for better signal reception with maximum possible link distance between the sender and the receiver keeping variable attenuation environment. The frequency of operation is 1550nm throughout the processes. In this work, several digital modulation techniques and optical filters for receiver are designed and simulated. The better resulting modulator and filter design in terms of high Quality factor and low bit error rate are considered and is integrated with each other. The Signal to Noise Ratio (SNR) and optical SNR are calculated for the integrated design theoretically. Higher the SNR less will be BER and hence the signal connectivity can be improved in the high speed free space optical communication systems.*

Keywords: *Free space optics, 5G data transmission, signal to noise ratio, bit error rate, quality factor.*

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1. Introduction

In our digital era, the importance of knowing possible channels of telecommunication systems and the ways of new transmission links in market to enhance the quality of user experience is necessary. The various channels of optical communication can be categorised into guided system channel and unguided system channel. Guided channels have low attenuation and low dispersion rate since the fiber is conserved. Repeater spacing allocation for guided system is large. The communication link is not subjected to electromagnetic interference since optical fiber connects the transmitter and the receiver [1, 17]. The possibility of cross talk is less but it has poor source efficiency with limited power. In case of accessing capability, Guided channel do not support multiple accesses directly. Underground telecommunication cables are best examples of Guided channels [5]. Unguided channels has higher ratio of received power to transmit power with smaller transmitter and receiver apertures. Free Space Optical communication (FSO) connects transmitter and receiver by wireless communication. Underwater and space communications are best examples of Free space optical communication [4, 15, 16]. Unguided systems have less beam acquisition than Guided systems

The need for large bandwidth and high data rate is increasing day by day [9]. Optical communication media is providing higher bandwidth than coaxial cable and twisted pair cables. The coaxial cable shares the frequency of 30MHz to 300MHz in Electromagnetic spectrum and waveguides shares frequency of about 3GHz to 300GHz whereas optical fiber shares the frequency of 30THz to 300THz in electromagnetic spectrum [8, 18]. Free space or satellite communication is complementary to fiber optics and both have its own peculiar features [6, 20].

2. Ideal FSO Connectivity Architecture

Getting ideal results depend on the fairness of the internal and external factors. The external factors include noises and atmospheric turbulences. The internal factor carries the role of efficient optical design structures [21]. The desirable characteristics of optical sources includes narrow spectral width, the capability to couple power to fibers, High speed, linearity in modulation, good reliability and light emission within low loss window of spectrum. Light Emitting Diode (LED) or visible light source is having smaller life time compared to the infrared coherent laser sources [2]. Fiber optical communication transmission involves transmission of light in form of ray, photon and in waveform. Though there are several representation of light signal, the characteristics of the light is similar in all cases. The electrical binary pulses are converted into optical signal and then it is allowed to pass through optical fiber [3]. Modulation is the important phenomena in transmission. Depending on the modulation techniques the input information signals will undergo different process in terms of phase, amplitude and frequency [12]. Now a day's various digital modulation techniques offers fast and efficient transmission. The modulator at the transmitter will encode the information bits before sending it through optical channel or wireless channels [11, 19]. In free space optical communication after transmission into the channel, attenuation effect is considerably more and so proper mitigation and non linear compensation has to be made. The channel takes place a major role in reaching out to the receiver. The noise attacking probability is very high at the channel than any other optical signal transmission blocks [9, 13, 22]. There are various filters available for removing high frequency noises which are discussed later in the paper. The received signal strength varies on the factor of terrain surface of the installed transmitter antenna and the receiver antenna [12]. The 3R performs reshaping, retiming and reamplification on the received data pulses. The pulses are reshaped and then it is reamplified with 3R regenerator. Free space optics is a flexible network that provides better speed than broadband and it offers spatial reuse [7].

3. Proposed Methodology

The design structure for the proposed method is shown in the following Figure 1. The design is simulated using optical design software tool from optiwave product. Continuous wave and machzehnder amplitude modulators usages are eliminated in the paper. This model sends the digital information signal bits which are generated by Pseudorandom Sequence Generator (PRBS).

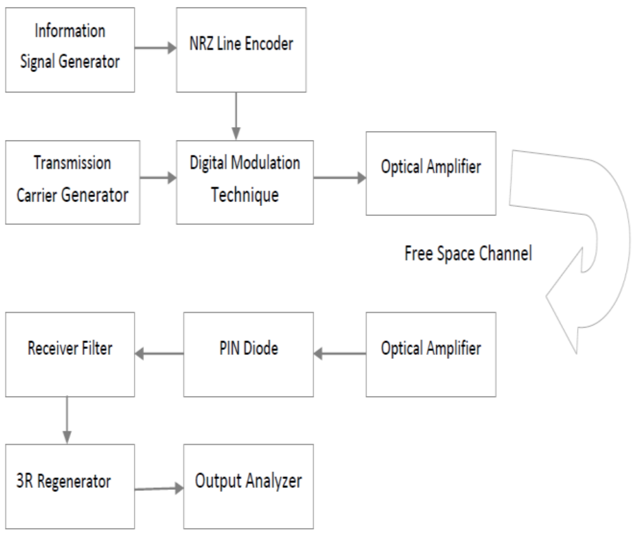

Figure 1. Proposed integrated layout of point to point long reach FSO systems.

The bit sequence will be sent to approximate the characteristics of random data. The signal input type is electrical which produces the digital message signal say f_m. PRBS generator with order k is used to generate a sequence with period of 2k-1. Digital data are encoded by popular line encoding methods like Return-to-Zero (RZ), Non-Return-to-Zero (NRZ). The Fatadin *et al.* [10] compared performance of NRZ and conventional On-Off Keying (OOK) are analysed in optical fiber, Among that NRZ is better than OOK in terms of Q factor and maximum distance is achieved as a result . The transmitted signal by keeping the rise time and fall time values to be 0.05 and duty cycle as 0.5 respectively. The optical carrier signals say f_c which is the analog signal generated by the optical transmitter. The frequency of the design range is 1550nm or 193.1 THz. The particular reason for choosing this window in electromagnetic spectrum is because it is a low loss emission window than going upscale or downscale. The digital modulation schemes enable FSO to transmit the information signal to a large extent than analog modulations. Digital modulation techniques like Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK) are compared for proposed integrated 5G design FSO system. The Q factor and Bit Error Rate (BER) are analysed. The SNR is theoretically calculated and verified for the integrated proposed system [23].

The attenuation rate of 0.5 dB/km falls under clear to haze condition [2]. The optical pumping source for amplifying the transmitting signal is essential to carry forward the signal via unguided channels. In this proposal, simple cost efficient optical amplifiers with gain of 20dB and Noise figure of 4dB is chosen. The pre and post amplification is essential to avoid the signal from signal loss [14] and to increase the sampled clock rate because of high frequency modulating signals. The FSO channel test range is 1km. The transmitter aperture diameter range is 10cm and receiver aperture diameter range is 10 cm. Beam divergence of the channel is 2mrad. At the receiver, the proposed filters are used with zero insertion loss.. The Bessel filter has the flat phase and group delay. It shows shallow frequency bands. The Bessel filter transfer function is given in Equations (1) and (2).

$$H(s) = \frac{\propto d_0}{B_N(S)} \tag{1}$$

$$d_0 = \frac{(2N)!}{2^N N!} \tag{2}$$

Where α is the parameter insertion loss, N is the parameter order and $B_N(s)$ an nth-order bessel polynomial.

The ripples due to the noise will be filtered. Chebyshev filter has the steepest roll off. The input and output of a chebyshev filter will be optical signal. The transfer function magnitude of chebyshev filter is given in Equations (3) and (4).

$$|H(s)| = \frac{1}{\sqrt{1+\frac{\omega}{\omega_0}T_n^2\varepsilon^2}} \tag{3}$$

Where ε is the ripple wave factor, ω_0 is the cutoff frequency, δ is the ripple frequency and T_n is the n[th] order Chebyshev polynomial.

$$\varepsilon = \sqrt{10^{\,0.1\delta} - 1} \tag{4}$$

Butterworth filter has slower roll off than chebychev filter. The order of the filter used for testing filter performance is 1 with the multiplication factor 1.1989. The transfer function for Butterworth filter is given in Equations (5) and (6).

$$H(f) = \alpha \frac{f_c^N}{\prod_{k=0}^{N-1}(j(f)-p_k)} \tag{5}$$

$$p_k = f_c . e^{j\frac{\pi}{2}(1+\frac{2k+1}{N})} \tag{6}$$

Where α is the parameter Insertion loss, f_c is the filter cutoff frequency, N is the parameter order and f is the frequency.

The input and output of a Fabry perot filter is optical signal. The number of frequency points used for calculating filter frequency response is 1024. The Fabry Perot filter transfer function is given in Equations (7) and (8).

$$H(f) = \alpha \frac{1-R}{1-R*e^{2\pi l \frac{f-f_c}{B}}} \tag{7}$$

$$R = \frac{2+(\frac{\pi B}{FSR})^2 - \sqrt{\left(2+\left(\frac{\pi B}{FSR}\right)\right)^2 - 4}}{2} \tag{8}$$

Where *H(f)* is the filter transfer function, *α* is the insertion loss, *fc* is the filter center frequency. *B* is the bandwidth, *f* is the frequency and *FSR* free spectral range.

Apart from filtering, Trapezoidal filter will act as a pulse shaping component and prevents pulse broadening of the signal. Pulse broadening will cause the spectral width to become larger and makes amplitude to vary with original signal. The transfer function of Trapezoidal filter is given in Equations (9) (10), and (11).

$$H(f) = \left\{ \alpha 10^{\left(\frac{1-A}{10B-B_{0dB}}\right)(f-f_2)} ; \quad f>f_2 \right\} \tag{9}$$

$$H(f) = \{\alpha \; ; \; f_1 < f_c < f_2\} \tag{10}$$

$$H(f) = \left\{ \alpha 10^{\left(\frac{1-A}{10B-B_{0dB}}\right)(f-f_1)} ; \; f>f_1 \right\} \tag{11}$$

Where *H(f)* is the filter transfer function, α is the insertion loss, fc is the filter center frequency defined by the parameter frequency, *B* is the bandwidth at the cutoff magnitude, B_{0dB} is the zero *dB* bandwidth, and f is the frequency.

The input and output port of a Rectangular filter are Electrical signals. This filter is unidirectional. The number of frequency points used for calculating filter frequency response is 1024. In this simulation evaluation bandwidth of the filter is kept to be about 2nm.

Table 1. Receiver side filter analysis.

Receiver Filter type	Max. Q Factor	Min BER	Eye Height	Receiver Threshold
Bessel Filter	4684.42	0	5.93326	0.135857
Chebyshev Filter	2010.93	0	5.9301	0.0486771
Butterworth Filter	165.78	0	0.00185609	0.000104694
Fabry Perot filter	287.241	0	0.00686232	0.000121519
Trapezoidal Filter	161.203	0	0.0504044	0.000192319
Rectangular Filter	48.9998	0	7.17687	2.93884

Table 1 show the receiver side filter performance analysis of various filters with maximum possible Q factor. The values are tabulated for better reachability distance up to 2km.

The following Table 2 shows the results of Amplitude Shift keying modulator with the corresponding speed of 4G LTE(10Gpbs) and 5G (50Gpbs) speeds. From the Table 2 we can conclude that as the distance increases, the power and data rate had to be high in order to transmit signals with good Q factor. For 5G speed with 1 km, Q factor of 20.4736 is achieved.

Table 2. Amplitude shift keying modulator analysis.

Data Rate	Distance (Km)	Power (dbm)	Attenuation (dB/km)	Max Q Factor	Min BER	Eye Height
2.5 Gbps	6	30	3 (Heavy fog)	15.0286	2.37093e-051	0.0123195
5 Gbps	5	40	2 (Light fog)	19.8073	1.13815e-087	0.156871
10 Gbps	3	45	1(Moderate rain)	20.363	1.47047e-092	0.19489
20 Gbps	2	47	0.7 (Haze)	20.494	1.00197e-093	0.257248
50 Gbps	1	50	0.5(Clear)	20.4736	1.51555e-093	0.856381

Table 3. Outcome of frequency shift keying modulator.

Data Rate	Distance (Km)	Power (dbm)	Attenuation (dB/km)	Max Q Factor	Min BER	Eye Height
2.5 Gbps	6	30	3 (Heavy fog)	41.1625	0	0.0123056
5 Gbps	5	40	2 (Light fog)	298.528	0	0.0850717
10 Gbps	3	45	1(Moderate rain)	919.604	0	0.109819
20 Gbps	2	47	0.7 (Haze)	1049.58	0	0.175029
50 Gbps	1	50	0.5(Clear)	1362.06	0	0.857757

The Table 3 reveals the result of Frequency Shift keying modulator with corresponding 4G LTE (10Gpbs) and 5G speeds (50Gpbs). For 5G speed with 1 km distance, Q factor of 1362.06 is achieved.

Table 4. Result of phase shift keying modulator.

Data Rate	Distance (Km)	Power (dbm)	Attenuation (dB/km)	Max Q Factor	Min BER	Eye Height
2.5 Gbps	6	30	3 (Heavy fog)	39.6026	0	0.0122654
5 Gbps	5	40	2 (Light fog)	292.923	0	0.0849329
10 Gbps	3	45	1 (Moderate rain)	942.816	0	0.109672
20 Gbps	2	47	0.7 (Haze)	1042.66	0	0.17486
50 Gbps	1	50	0.5(Clear)	1359.2	0	0.857596

The Table 4 illustrates the result of Phase Shift keying modulator with corresponding 4G LTE (10Gpbs) and 5G speeds (50Gpbs). For 5G speed with 1 km distance, Q factor of 1359.2 is achieved.

4. Improved SNR and OSNR for Better Connectivity in FSO Systems

Based on the individual performance of digital modulators and receiver filters in 50 Gbps speed, it is obvious to reveal that PSK and FSK modulator holds good for long range optical systems. Bessel filter and Chebyshev filter have the highest Q factor with reduced BER. By the overall comparison of the obtained results, the integrated designs of FSK with Bessel, PSK with Bessel filter, FSK with Chebyshev filter and PSK with Chebyshev filters are designed and simulated. The spectrum outputs of the integrated design is shown in Figurs 2, 3, 4, and 5. We calculated the equivalent signal- to- noise ratio for proposed system.

The channel SNR and optical SNR are calculated by using the formulas given in Equations (12), (13), (14), and (15). The corresponding values are recorded by the power meter component of the simulation.

In terms of Power, *SNR* is

$$SNR_{dB} = 10 \log \frac{P_s}{P_n} \quad (12)$$

In terms of Voltage, *SNR* is

$$SNR_{dB} = 20 \log \frac{V_s}{V_n} \quad (13)$$

If all levels are expressed in decibels then,

$$SNR = P_{Signal\ (dB)} - P_{Noise\ (dB)} \quad (14)$$

$$OSNR = 10 \log \frac{P_s}{P_n} + 10 \log \frac{B_m}{B_r} \quad (15)$$

B_m is Equivalent noise bandwidth

B_r is Reference optical Bandwidth ≈ 0.1 nm

4.1. FSK with Bessel Filter SNR & OSNR Calculation

The computation of Signal to noise ratio and Optical signal to noise ratio for FSK with Bessel filter is calculated as

SNR (dB) =Signal power – Noise Power
=46.616197-(-4.6671706)
= 51.283368 dB
OSNR(dB)=Signal power– Noise power at 0.1nmdB
=46.616197 –(- 13.69807)
=50.3888696 dB

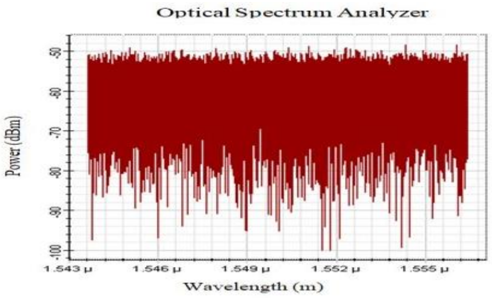

Figure 2. Spectrum output of FSK with Bessel filter.

4.2. PSK with Bessel Filter SNR & OSNR Calculation

The calculation of Signal to noise ratio and Optical signal to noise ratio for PSK with Bessel filter is formulated as

SNR (dB)=signal power – Noise Power
=46.466972- 5.1091759
=41.357796 dB
OSNR=Signal power – Noise power at 0.1nmdB
=46.466972 –(- 3.9217239)
=50.3888696 dB

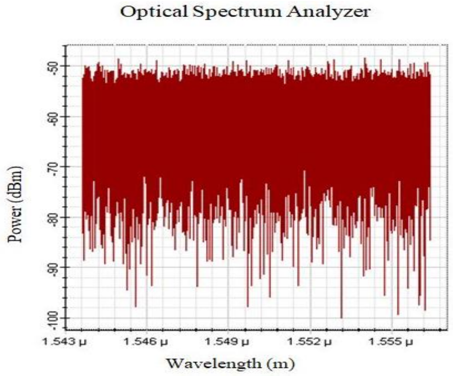

Figure 3. Spectrum output of PSK with Bessel filter.

4.3. FSK with Chebyshev filter SNR & OSNR Calculation

The computation of Signal to noise ratio and Optical signal to noise ratio for FSK with Chebyshev filter is formed as

SNR (dB)=Signal power – Noise Power
=46.616197-(-4.6671706)
= 51.283368 dB
OSNR=Signal power – Noise Power
=46.616197 –(- 13.69807)
=50.3888696 dB

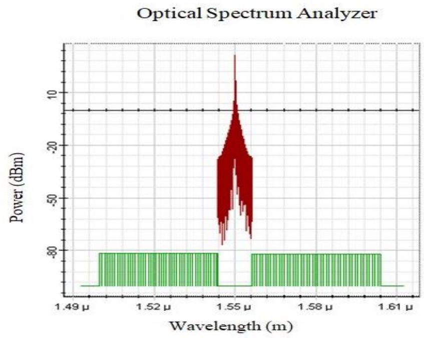

Figure 4. Spectrum output of FSK with Chebyshev filter.

4.4. PSK with Chebyshev Filter SNR & OSNR Calculation

The working out of Signal to noise ratio and Optical signal to noise ratio for PSK with Chebyshev filter is calculated as

SNR (dB)=Signal power –Noise Power
=36.80277-(-13.610159)
=50.412929 dB

OSNR = Signal power – Noise Power at 0.1nmdB
=36.80277 – (-18.661659)
=55.464429 dB

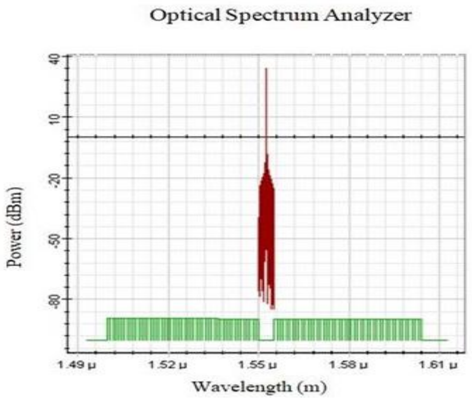

Figure 5. Spectrum output of PSK with chebyshev filter.

Table 5. Consolidated proposed system outcome.

Data Rate: 50 Gbps	Frequency: 1550nm	
Integrated Design Type	**Max. Q**	**SNR (dB)**
FSK with Bessel filter	2260.33	51.283368
PSK with Bessel filter	2274.77	41.357796
FSK with Chebyshev filter	4859.05	51.283368
PSK with Chebyshev filter	5024.3	50.412929

The Table 5 explains the final outcome of the proposed system for a distance of 1km. From the table it is observed that the power of the system is 30 dB at 3dB/km attenuation.

5. Conclusions

The connectivity of 5G high speed FSO systems is thereby upgraded with maximum SNR and Q factor considering best repeater spacing in simulation. The proposed integrated model with distance 1 km and data rate 50Gbps, achieved maximum of 4000 Q factor with 0.5dB/km clear environment. Further if the distance increases, there is a decline in Q factor. For a distance of 6kms and above with 5G speed, Q factor of 200 is achieved. This paper focused to use digital modulation with 5G data rate together with various optical filters. Since the attenuation of the atmosphere has its considerable effect in free space optical transmission, various filter performance are analysed with digital keying modulations to eradicate the maximum noise present in transmission.The analysed resultant Q factor and eye distance of the model is highly agreeable. The bit error rate is minimised as much as possible. Above 40dB SNR and 50 dB OSNR are obtained which is highly recommended for high speed optical data network connections. The Quality factor with 50 Gbps for ASK is 20, above 1000 with both FSK and PSK by considering minimum attenuation. These Q values can further be enhanced by using multiple input and multiple output transceivers methods.

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