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Performance Analysis of Radio Frequency Signals Over Optical Fiber for Wireless Communication Systems

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ABSTRACT- This paper investigates and analyses the performance of radio frequency (RF) signal over optical fiber for wireless communication systems in terms of bit rate, bit error rate (BER), quotient factor (Q-factor), signal strength and length of transmission. The RF signal is transported over optical fiber using direct Intensity Modulation – Direct Detection (IMDD) technique. The simulations are implemented for the bit rates (bandwidth) within the range of 0.5Gbit/s to 15Gbit/s and length of 30km, 50km and 70km. The output shows that increase in the bit rate for a given length of optical fiber indicates an increase in the minimum bit error rate (BER) and decrease in the maximum quotient-factor (Q-factor). Also, as the length of the optical fiber increases, the maximum Q-factor and eye height decrease. In view of this, it is advisable to effectively transport RF signals of less bandwidth (0.5 -5Gbit/s) over the optical fiber for a short distance communication system by direct intensity modulation. Higher bandwidth (above 5Gbit/s) can be transported within the design specifications, but a typical regenerator (repeater) should be installed at a periodic length (at least 50km interval) of the optical fiber. The use of Optiwave System as a simulation tool is found useful for the software implementation of the system to generate the BER patterns for direct IMDD technique.

Keywords: Continuous wave laser, Direct detection, Intensity modulation, Optical fiber, Photodetector, Radio frequency.

1. Introduction

The development of radio frequency over optical fiber is an innovation in technological advancement that integrates broadband wireless and fiber optic technologies which enables access network infrastructure for better network coverage, higher data rate, increases user capacity and faster access network as demanded by the intensive multimedia and real-time applications of telecommunication systems of nowadays such as WLAN, satellite communication system and mobile broadband services (Zin, et al, 2010).

The application of optical fiber in wireless communication is expressed in the form of radio frequency over optical fiber (RoF) which is the technology whereby light intensity is modulated by radio frequency signal and transported over optical fiber (Hamin and Sevia, 2007). It utilises optical link for analog transmission system since it transports the radio waveform from a central control station (headend) to a remote access unit (RAU). The process is repeated in opposite direction for a full-duplex operation. The major requirements of a radio frequency over optical fiber link architecture include optical transmitter, optical receiver, optical fiber length, full-duplex operation and radio frequency in the base station (Zin, et al, 2010).

The applications of RoF system include indoor wireless access network due to its limited dynamic range, the spurious free dynamic range (SFDR) uplink is about 50dB, whereas the SFDR uplink for the free space access network coverage is greater than 70dB (Visani, et al., 2009). RoF system is also very useful for mountainous areas, man-made obstacles, underground train tunnels and underground house apartment access wireless network infrastructures.

2. Fiber Optic Technology

Fiber optical technology is a technology that uses either strands of glass or plastic fiber to transmit data from one location to another. The optical fiber is capable of transmitting signals modulated into optical signals (Jeff, 2005). Fiber optics is made up of glass or plastic dielectric material. It consists of central part called core which has a higher refractive index and cladding of lower refractive index (John, 2009). The Fig. 1 below shows the diagram of light signals passing through optical fibers.

Fig.1: Light signals travelling in optical fiber cables.

Optical fiber cable is a guiding medium for light signal to transmit data from one point to another. Light wave is transmitted through the optical fiber by a principle called total internal reflection. The optical fiber contains a central part called core and surrounded by a cladding that has a lower refractive index (John, 2009).

Two conditions must be satisfied for total internal reflection of light to occur in an optical fiber (Jeff, 2005). These conditions are as follows;

i. The core's refractive index (n_1) should be higher than the refractive index of the cladding (n_2). That is, $n_1 > n_2$.
ii. The angle of incident (Θi) should be greater than the critical angle (Θc). That is, $\Theta i > \Theta c$.

From mathematical point of view, the amplitude of one wave component is represented by a scalar wave component (Jeff, 2005). The scalar wave component is also represented by a scalar wave function (u) which depends on time (t) and space (r). Due to total internal reflection, light ray is reflected at the core-cladding boundary and returns to the core lossless, which enables light propagation through the fiber (John, 2009). The Fig. 2 below shows the light propagating in the waveguide.

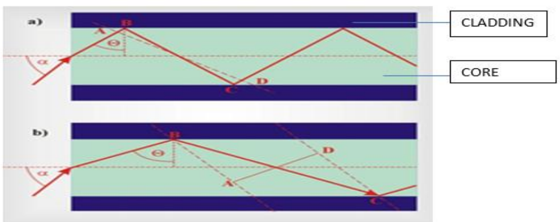

Fig. 2: Light propagating in the waveguide

The light signal originates from the laser or light emitting diode (LED). Electric signal on entrance is turned into optical signal in a transmitter, modulating light intensity at the same time. The light signal sent to the optical fiber propagates in the core with speed, *v*, of about 200,000,000 m/s (speed of light in glass). The refraction index for a typical glass is n ≈ 1.52; $v = \frac{c}{n}$, in order for the optical signal to successively get to receiver (PIN - photodiode or avalanche photodiode), where the optical signal is turned back into electric signal (John, 2009).

Fiber transmission modes are physical or mathematical concepts that explain the transmission of light signal in form of electromagnetic waves through the fiber. These mathematical theories are derived from Maxwell's equations which form the fundamental of electromagnetic theory (John, 2009). Light signal is propagated in an optic fiber in form of electromagnetic waves. The permeability and permittivity of the fiber define how the light signal travels in it.

Optical Communication system is the system and techniques with which optical fiber communicates information (data) from one point to another (John, 2009). In order to build an optical communication system, some components are needed such as switches, connectors, filters, amplifiers, better modulation schemes and so on (Al-Raweshidy, et al, 2002). Many techniques have been proposed and worked upon in optical communication system such as wavelength division multiplexing technique, optical amplifier technique, optical switches and filter techniques, coherent modulation scheme technique and so on.

The elements of optical communication system include transmitter stage, optical fiber and receiver stage. From the block diagram shown in figure 2.3, electrical input signal through a typical drive circuit is used in modulating the optical source. Once the light source is modulated, the optical signal is then transmitted through the optical fiber (John, 2009).

Depending upon the length through which the signals will travel, size of data and modulation format, a typical regenerator (repeater) is installed at some periodic length of the optical fiber. At the regenerator, there is signal conversion. The signal is converted from the optical domain to electrical domain where the signal is processed by signal processing electronic before the electrical signal is used to modulate the light source in optical transmitter of the regenerator and re-transmit through the optical fiber. The process continues depending upon the length of the optical link (John, 2009; Zin, et al, 2010)

Eventually at the receiver, there is a suitable optical amplifier depending upon the strength of the signal received. Photodetector converts the received optical signal to its original electrical signal. During the process of transmission, there are various signal losses such as attenuation and dispersion that need to compensate against as a communication engineer. The Fig. 3 below shows a block diagram that illustrates the component elements of optical communication system (Zin, et al, 2010).

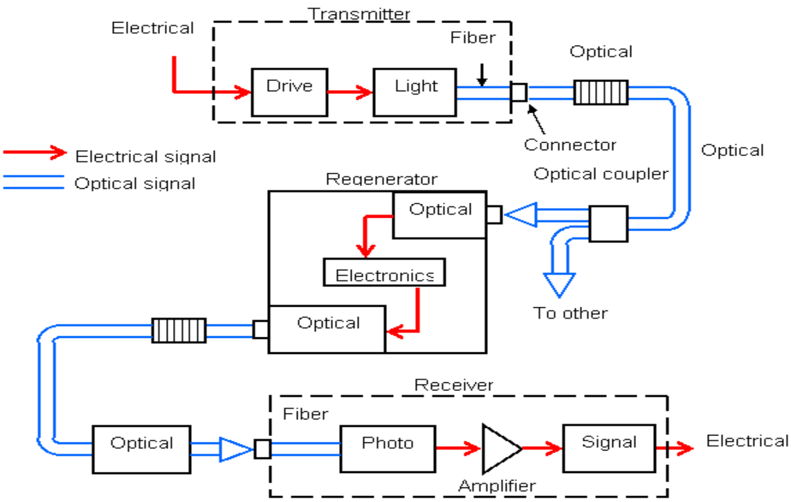

Fig. 3: Elements of optical fiber communication system

3. Methodology

The system design technique adopted for this work is Intensity Modulation and Direct Detection (IMDD) technique due to its simplicity, transparency to the modulation formats, possibility of sub-carrier multiplexing and its ability to incorporate external modulator in to the system. In IMDD technique design, the following items are needed;

i. **Optical transmitter** containing the pulse generator, CW laser and modulator to generate the intensity modulation.
ii. **Single mode fiber** (SMF).
iii. **Optical receiver** based on direct intensity modulation by the photodiode, demodulator and RF amplifier.

The laser diode in the optical transmitter generates electrical field which is exhibited in intensity modulation. The electrical field takes the form of the following mathematical modelling representations

$$e_{in}(t) = F(i_{in}(t)t) = E_0\sqrt{1+m_{Iav}i_{in}(t)}\, e^{j2\pi\left[f_0 t - K_f m_{Iav}(I_{LD}-I_{th})\int_{-\infty}^{t} i_{in}(r)dr\right]} \quad (1)$$

where E_0 = Field amplitude without RF modulator, I_{LD} = Bias current of the transmitter, I_{th} = Threshold current of the transmitter, K_f = Frequency modulation index, f_0 = Optical carrier, m_{Iav} = Mean optical modulation index, $i_{in}(t)$ = Normalised RF modulating signal, The normal current $i_{in}(t)$ is written as follows:

$$i_{in}(t) = I(t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t) \quad (2)$$

where fc = carrier frequency, I(t) = In-phase base band signal, Q(t) = Quadrature base band signal.

For practical purpose, using equation 3.2 in 3.1; then electrical field $e_{in}(t)$ can be approximated as follows;

$$e_{in}(t) \approx E_0\sqrt{1+m_{Iav}i_{in}(t)}.\, e^{j2\pi f_0 t}.\, e^{j\frac{K_f m_{Iav}(I_{LD}-I_{th})}{f_c}[I(t)\sin(2\pi f_c t)+Q(t)\cos(2\pi f_c t)]} \quad (3)$$

Also, the transmission of the optical signal in the single mode fiber employing the second order chromatic dispersion to obtain the following transfer function (D. Wake, 2002);

$$H(f,z) = e^{-\alpha(f_0)z}.\, e^{j\left\{\beta(f_0) + \tau_g[2\pi(f-f_0)] - \frac{\lambda_0}{2\omega_0}D[2\pi(f-f_0)]^2\right\}z} \quad (4)$$

where $\alpha(f_0)$ = Attenuation coefficient, $\beta(f_0)$ = Propagating coefficient, f_0 = Optical carrier frequency, τ_g = Group delay, λ_0 = Optical wavelength, ω_0 = Optical angular frequency, z = Fiber length, D = Second order dispersion coefficient (sec/m^2)

Finally, the optical receiver containing the photodiode detects the optical power through direct detection and the photo-detected current, $i_{out}(t)$ is given as follows;

$$i_{out}(t) = R|e_{out}(t)|^2 \quad (5)$$

where R = Responsivity of the photodiode.

The RoF system is designed with Optiwave System. The transmitter of the system is designed for direct modulation. The laser power input is set 0dBm, the laser operating frequency is 193.1THz and the laser linewidth is 10MHz. The optical link is set to fiber attenuation of 0.2dB/km and reference wavelength of 1550nm. The optical receiver is set to responsivity of 1A/W, dark current of 10nA and the low pass butterworth filter is set to cut-off frequency of 0.75*symbol rate.

The system is implemented for bit rates of 0.6, 0.7, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15Gbit/s and optical fiber length of 30, 50 and 70km. Fig. 4 below shows the design topology for direct modulation system.

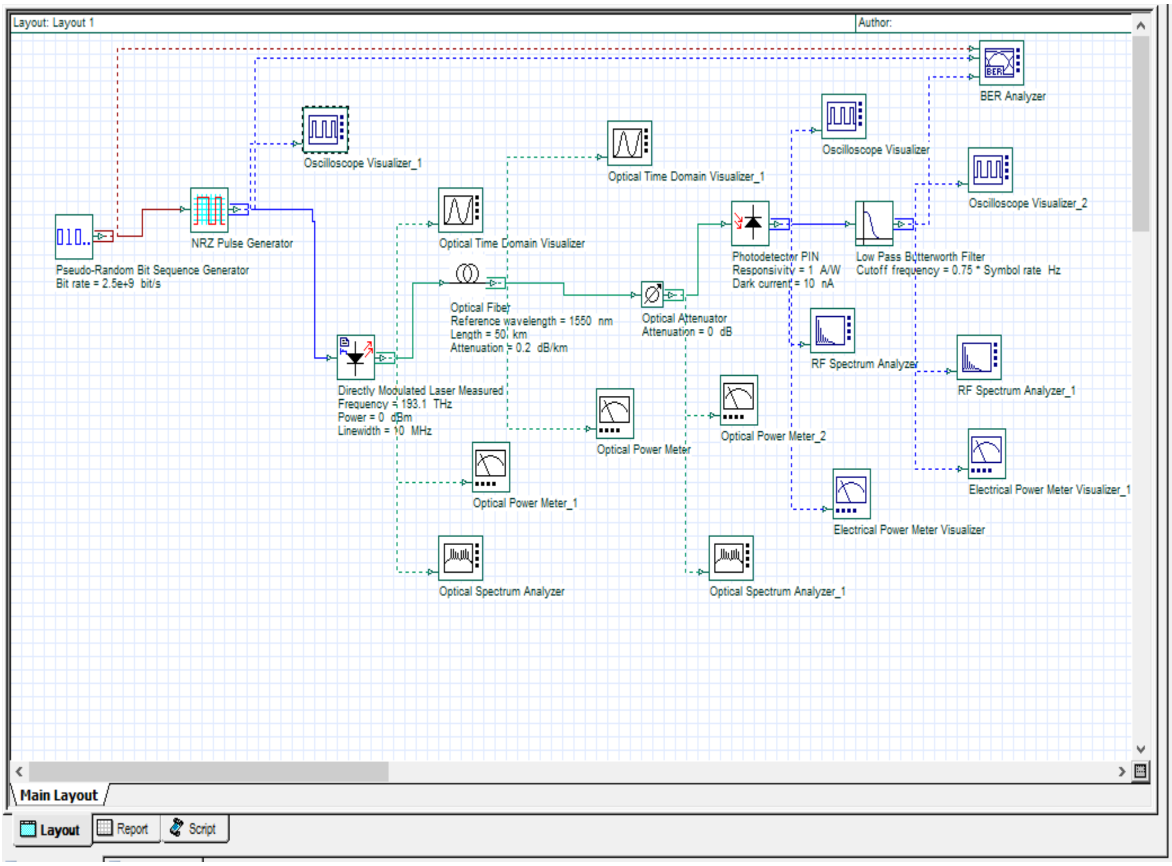

Fig. 4: Direct Intensity Modulation Design Topology

Design specifications for experiment:

Table 1: Table of design specifications for experiment

PARAMETERS	**VALUES**
OPTICAL TRANSMITTER	
Laser power input Laser operating frequency Laser Linewidth Bit rate	0dBm 193.1THz 10MHz 0.6 – 15Gbit/s
OPTICAL LINK	
Length Fiber Loss (attenuation) Fiber dispersion constant Reference wavelength	30km, 50km and 70km 0.2dB/km 16.75ps/nm/km 1550nm

OPTICAL RECEIVER	
Responsivity type	Constant
Responsivity	1A/W
Dark current	10nA
Thermal noise	100e-024
Low pass butterworth filter (cut off frequency)	0.75*symbol rate
Insertion loss	0dBm

4. Results and discussions

The simulation results for optical fiber length of 50km when the bit rate is varied from 0.6Gbit/s to 14Gbit/s are shown in the figure 5.1 (a - h) below. The following observations are made from the patterns and readings obtained from the BER Analyser:

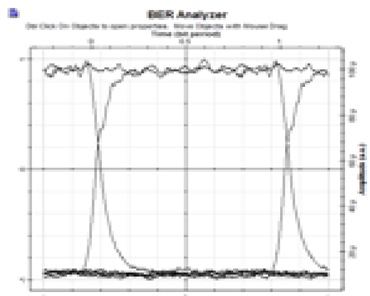

Fig. 5a: For bit rate of 0.7 Gbit/s

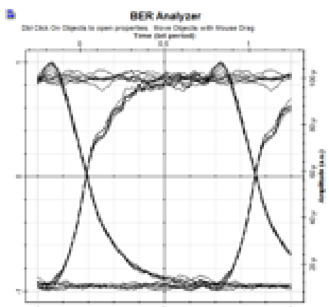

Fig. 5b: For bit rate of 2.0 Gbit/s

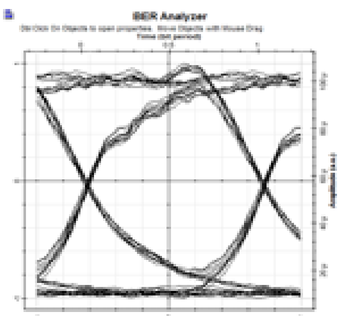

Fig. 5c: For bit rate of 4.0 Gbit/s

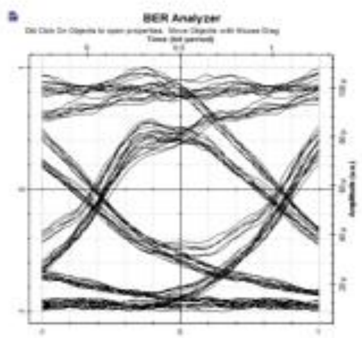

Fig. 5d: For bit rate of 6.0 Gbit/s

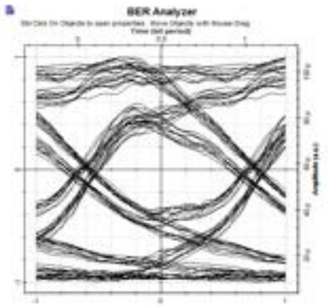

Fig. 5e: For bit rate of 8.0 Gbit/s

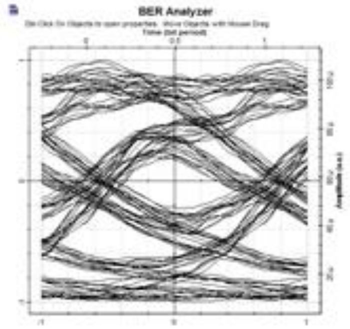

Fig. 5f: For bit rate of 10.0 Gbit/s

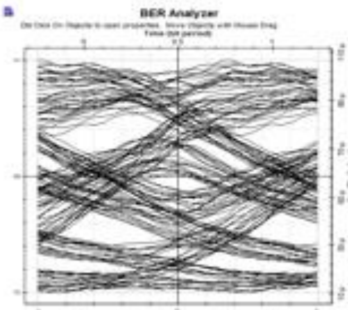

Fig. 5g: For bit rate of 12.0 Gbit/s

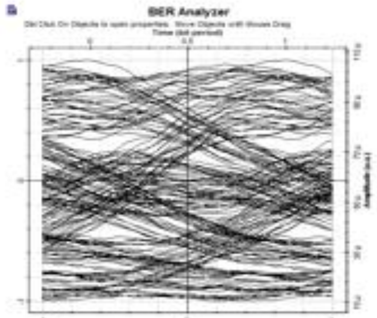

Fig. 5h: For bit rate of 14.0 Gbit/s

Discussions:

i. Figure 5 (a - d) with bit rates of 0.7Gbit/s to 6Gbit/s show good performance of the system as the eye heights are wide with relatively high values of maximum Q-factor.
ii. Figure 5 (e - f) with bit rates of 8Gbit/s to 10Gbit/s show that the performance is low as the eye height is becoming closing, the values of minimum BER is increasing and maximum Q-factor is decreasing.
iii. Figure 5 (g - h) with bit rates of 12Gbit/s to 14Gbit/s show that the performance is worst as the eye height is closed, the minimum BER is highly and maximum Q-factor is approaching zero.

Performance Analysis

The graphs depicted in Figs. 6 – 10 are plotted to analyse the performance of the system in experiment. The graphs is plotted to compare the performances of maximum Q-factor, minimum BER, eye height, threshold and decision instant when the bit rate is varied for optical length of 30km, 50km and 70km as follows;

(i). Graph of Maximum Q-factor against Bit rate for 30km, 50km and 70km

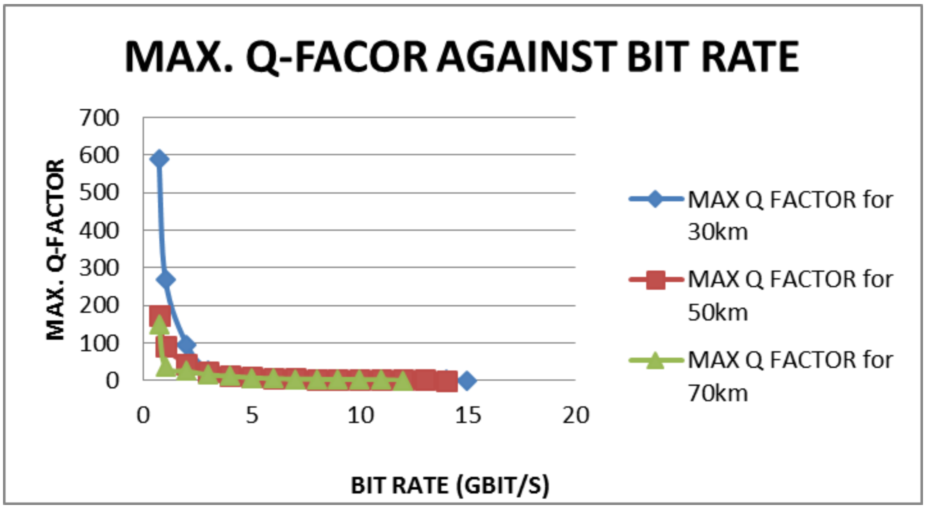

Fig. 6: The graph of Max. Q-factor against Bit rate for 30km, 50km and 70km.

As shown in Fig. 6, the value of maximum Q-factor is high at bit rate less than 2.0Gbit/s for optical fiber length of 30km. At bit rate of 3Gbit/s, the maximum Q-factor is almost the same for optical length of 30km, 50km and 70km. The Q-factor drastically reduces and approaching zero after the bit rate of 5Gbit/s.

(ii). Graph of Minimum BER against Bit rate for 30km, 50km and 70km.

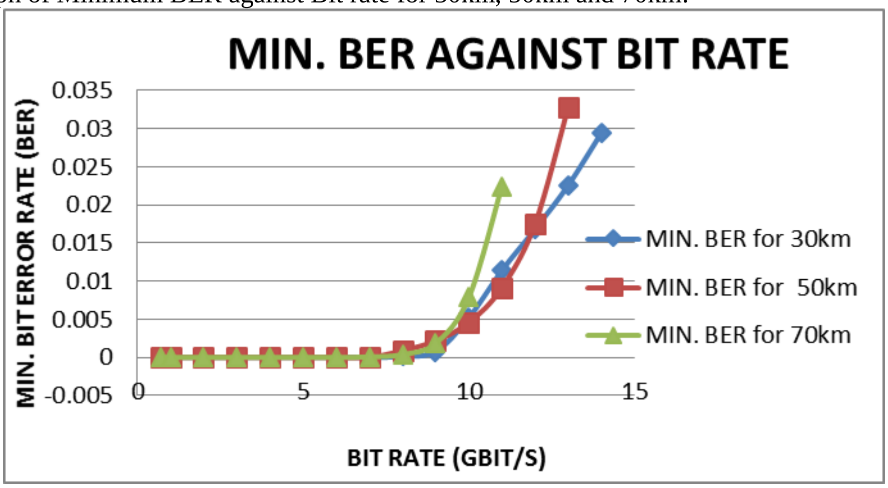

Fig. 7: The graph of Min. BER against Bit rate for 30km, 50km and 70km.

Figure 7 shows that the value of minimum BER is very low for the bit rates of 0.7 – 6Gbit/s. The minimum BER increases at theSS bit rate above 8Gbit/s.

(iv). Graph of Threshold against Bit rate for 30km, 50km and 70km.

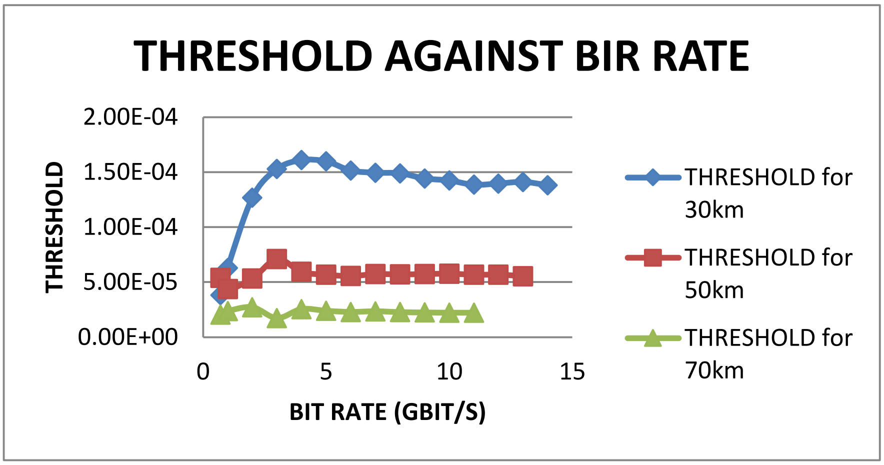

Fig. 8: The graph of Threshold against Bit rate for 30km, 50km and 70km

As shown in Fig. 8, the value of threshold is high for the bit rate of 3Gbit/s for optical length of 30km, relatively good at the bit rate of 3Gbit/s for 50km, but generally low for the optical length of 70km. The threshold increases as the optical fiber increases.

(v). Graph of Decision instant against Bit rate for 30km, 50km and 70km.

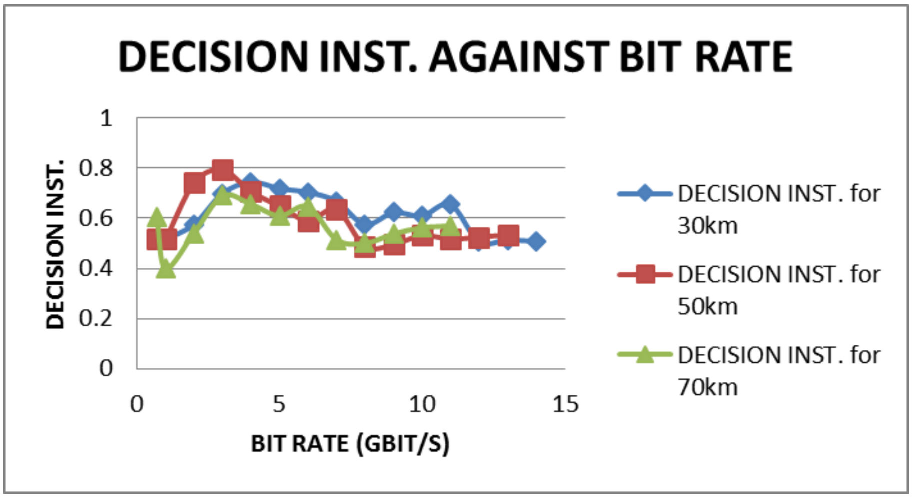

Fig. 9: The graph of Decision instant against Bit rate for 30km, 50km and 70km

Figure 9 shows that the value of decision instant is very high at the bit rate of 3Gbit/s for optical fiber length of 50km and generally decreases as the bit rate increases.

Summary of the results:

A direct modulation of RoF system has been designed and implemented. Its performance has been analysed. It was observed that the maximum bit rate allowed for transmission over the optical fiber of 30km is 14Gbit/s, 50km is 13Gbit/s and 70km is 11Gbit/s.

The system performance is good at the bit rate of 0.7 - 5Gbit/s, though much better in 0.7 - 3Gbit/s. This is due to its high Q-factor, high eye height and low values of minimum BER. As the bit rate increases, the Q-factor decreases, the eye height decreases and the minimum BER increases for all the optical fiber length used.

5. Conclusions

The main focus of this work is achieved by investigating and analysing the performance of radio frequency signals over optical fiber using Intensity Modulation – Direct Detection (IMDD technique. This technique creates no phase noise, it is practically transparent, easy to implement, external modulator is easily incorporated and it is a cost effective technique of transporting radio frequency over optical fiber.

The simulation outputs show that radio frequency signals of bit rates (bandwidth) of 0.7 – 5Gbit/s can be transported effectively over the given optical fiber lengths of 30km, 50km and 70km. It also shows that if higher bandwidth (above 5Gbit/s) is to be transported within the design specifications, a typical regenerator (repeater) should be installed at a periodic length of the optical fiber.

Furthermore, the simulation outputs indicate that as the bit rate increases, the value of minimum bit error rate (BER) increases and the value of the maximum Q-factor decreases. Also, as the length of the optical fiber increases, the value of maximum Q-factor decreases, the eye height decreases and the signal strength loss at the receiver increases. The outcome of this research work makes it advisable to effectively transport radio frequency signals of less bandwidth over an optical fiber for a short distance communication by direct intensity modulation.

Further research work would be useful to investigate the performances of radio frequency over optical fiber by indirect intensity modulations. Moreover, comparative performance analysis of single mode fiber (SMF) and multimode fiber (MMF) transmission of radio frequency signals should be carried out. More detailed mathematical expressions and calculations would be appreciated with MATLAB scripting in the design of RoF system.

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