BER IMPROVEMENT FOR MULTI-GIGABITS-PER-SECOND FREE SPACE OPTICAL COMMUNICATIONS BY STABILIZING THE DECISION THRESHOLD LEVEL

S Hitam[1], M.K Abdullah[2], W.A Wan Adnan[1], B.S Sheikh Naimullah[3]
[1]Department of Computer System and Communication, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[2]Significant Technology Sdn. Bhd, No 12-1, 1st Floor, Jalan Dagang SB4/1, Section 4, Taman Sungai Besi Indah, 43300 Sri Kembangan, Selangor, Malaysia.
[3]Faculty of Electrical Engineering, UiTM Sarawak, Samarahan Campus, Jalan Meranek, 94300 Kota Samarahan, Sarawak, Malaysia
Email: salasiah@eng.upm.edu.my

ABSTRACT

A new transmission and detection technique namely Double Carrier Modulation/Differential Detection (DCM/Diff.D) for free space optical (FSO) is proposed. The technique employs two beams, one modulated with the data, the other with the inverted version of the same data. A differential detection technique is used at the receiver whereby the inverted data are used as the reference to perform the decision making, as opposed to the fixed threshold used in conventional technique. The probability of error under threshold instability in DCM/Diff.D technique and Intensity Modulation/Direct Detection (IM/DD) technique, is compared. A simulation under heavy rainfall condition of $8.33x10^{-4}$ cm/sec at bit rate of 2.5 Gbps with 0 dBm of optical transmitter power shows that this technique achieves an improvement of more then twice of distance of the conventional IM/DD.

Keywords: *differential detection, intensity modulation direct detection, free space optical, non-selective scattering, probability of error.*

INTRODUCTION

Recently, FSO receives growing attention for use in high data rates wireless link with recent commercialization success [1-3]. It is an interesting solution to achieve high bandwidth in economical and fast way in metropolitan. As an alternative to Radio Frequency (RF) and millimetre wave, it is widely believed that FSO is best suited for multi-Gbps communication. However, one of the biggest challenges facing FSO deployment is optical signal propagation in different atmospheric conditions. This effect will cause signal attenuation which can degrade the performance of links, particularly over ranges of several hundred meters or longer. It is typically dominated by fog but can also be dependent upon low clouds, rain, snow, dust, haze and various combinations of each.

The conventional technique that is IM/DD uses an injected voltage level as a threshold into a decision circuit, which decides whether the incoming bit is a 0 or a 1. When the data input voltage is higher than the threshold, a 1 bit is regenerated, and vice versa. However, this technique has two inherent problems; the instability of the injected threshold voltage, and the complexity of a dynamic threshold processing. As the threshold voltage has its own noise and fluctuation, it adds to the deterioration of the signal, thus limits the systems performance. Meanwhile, due to the random nature of the incoming bits, coupled with the masking noises and jitters, the threshold voltage level cannot be set at a fixed value, and therefore a dynamic voltage threshold adjustment is required [4].

In the last two decades, balanced receiver in coherent optical communications have been widely investigated [5 - 6] because of their superior characteristics over direct detection such as greater sensitivity [7] and enhanced frequency selectivity [8]. The greater sensitivity is necessary in the implementation of both optical fiber long-haul transmission links as well as inter-satellite free space links [9], while the greater frequency selectivity is an important feature in the wideband communication networks and multi-channel systems of the future [10]. In order to reach the theoretical sensitivity improvement mentioned above, it is necessary to operate in a shot-noise limited condition [11], a low thermal noise and high common mode rejection ratio (CMRR) to suppress relative intensity noise (RIN). Different designs are proposed to increase the receiver sensitivity and reduce the thermal noise power contribution at the photoreceiver output. One of them is to implement a balanced tuned photoreceiver [12]. Another method is to optimize the dual-detector heterodyne receiver by using a beam splitter to combine a weak received signal beam with a stronger local oscillator beam [13].

Regeneration circuits are a very important stage, where the decision is taken and bits sequence is regenerated. Winzer et al. [14] has reported that optimum decision threshold is significantly underestimated by Gaussian approximation in the case of single-ended differential phase-shift keying (DPSK) reception, while the minimum BER is reproduced to within an order of magnitude. This coincidence owes to the fact that while the error probability for a '0' bit is strongly underestimated by the Gaussian approximation, the '1' bit error probability is overestimated by the same amount. However, in the case of balanced detection, the confrontation is done with the detection of ±1 than of '0' and '1'. Thus, the compensating effect within the Gaussian approximation vanishes, and the BER predicted by the Gaussian approximation exceeds its exact value by several orders of magnitude. In [15], the authors claimed that the sensitivity of 4 dB in DPSK modulation is achieved well than for the OOK modulation format which is mainly attributed to the balanced detection scheme. The improvement is even larger than the expected 3 dB as reported in [16] using return-to-zero (RZ)-DPSK. RZ-DPSK modulation format has lower peak powers and constant amplitude. Therefore, by using balanced detection a system has a constant decision threshold and easier to optimize and more robust against degradations. The system, which can overcome the sensitivity and constant threshold, is desirable especially for OW communications where the distance is typically limited to 800 m in heavy rain at 2.5 Gbps [17].

In this paper, we use DCM/Diff.D technique to result in a virtual zero threshold voltage which can be set stably to provide an automatic and more accurate decision making, thus eliminating the complicated dynamic threshold process. The DCM/Diff.D is a technique based on modulation of two data (one is inverted from the other) and on the differential detection technique. Although differential techniques have been used before but similar approach to DCM/Diff.D has never been reported. It will be shown subsequently that DCM/Diff.D will improve the probability of error and extend FSO distance to more than twice significantly longer than that being the conventional IM/DD approach.

DESIGN CONFIGURATION

The concept used in DCM/Diff.D technique is the amplitude subtraction between the original signal, A1 with its inversion A2 carried by two different carriers. In this paper, the two carriers are modulated at the same time (assuming that the inverter delay is minimal) and are launched into separate transceivers as shown in Figure 1. This leads to the Double Carrier Modulation (DCM) term.

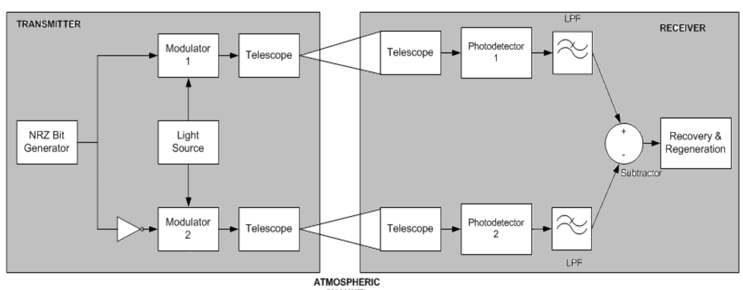

Figure.1: Simulation setup

In the simulation, the transceivers used were of the same type, length and properties. It is also assumed that the equal turbulence conditions for both channels during heavy rainfall. In reality, the transceivers cannot be exactly identical, thus a difference in propagation time will pose a problem at high transmission rates. However, it is believed that introducing a delay mechanism either optically or electrically, in the faster path can solve the problem.

The simplest method to get delay mechanism optically is by changing the separation w between the light source and the detector as shown in Figure 2. The time delay τ of the signal is simply given by $\tau = w/c$ which c is the speed of light. If the phase shifted signal was required electrically, as opposed to optical form, then it will be necessary to convert the electrical signal to light (with an LED or laser), then convert back to electrical with a photodetector of some variety, as shown in the same figure. By using this method, the signal propagation in the two channels can reach at the photodetector simultaneously.

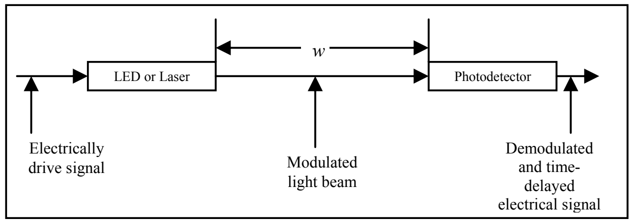

Figure 2: Delay mechanism optically or electrically

The original signal A1 and its inversion A2 are detected by photodetector 1, PD1 and photodetector 2, PD2 respectively and are converted to electrical voltage, V1 and V2. These two electrical signals will become the input of an electrical subtractor, which subtracts V2 from V1. The resultant signal will have positive and negative amplitudes, with absolute magnitude reaching double in value compared to the original received bits amplitude as shown in Figure 3.

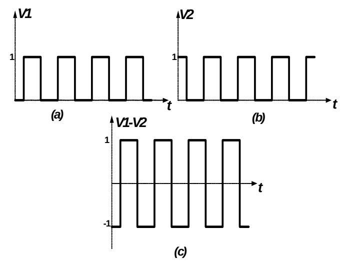

Figure 3: (a) Original bits, A1 (b) Inversion of original bits, A2 (c) The resultant subtracted bits

The subtractor outputs a 1 bit if V1 is larger than V2, and a 0 bit if V1 is smaller than V2. Note that no external DC voltage supply is required to be the referenced threshold voltage as in conventional systems. V2 itself automatically serves as the threshold whose value is always in reversal to that of the data, V1 (between mark and space levels). When V1 is a mark, V2 is a space and vise versa. Thus, since the difference between V1 and V2 is at the maximum, the first problem associated with threshold fluctuation and noise is minimized. At the same time, the automatic decision making is provided because both V1 and V2 themselves change together dynamically depending on the received optical power levels at receivers 1 and 2 respectively. Therefore there is no need for complicated automatic threshold control schemes such as the eye-pattern scanning method.

ENVIRONMENT FACTORS: A BRIEF REVIEW

Atmospheric Attenuation

In tropical country, rain dominates the total attenuation coefficient [18]. The attenuation due to rainfall is also called non-selective scattering since the drop size is much larger than the wavelengths making scattering effects wavelength independent [19]. In this simulation, the data was taken from the Malaysian Meteorological Department.

The atmospheric attenuation τ_a is described by the following Beer's law equation [20]:

$$\tau_a = e^{-(\beta_{abs}+\beta_{scat})R} \tag{1}$$

where, β_{abs} and β_{scat} are the absorption and scattering coefficient, respectively. R is the link distance. The total scattering by rain is given by [19]:

$$\beta_{scat}^{rain} = \sum_a \pi a^2 N_a Q_{scat}\left(\frac{a}{\lambda}\right) \tag{2}$$

where, Q_{scat} is the scattering efficiency, also referred to as the Mie attenuation coefficient. For ratios $a/\lambda>30$ the Q_{scat} is approximated as equal to 2. N_a is the number of drops of radius a in a unit volume (cm^3). Figure 4 below shows atmospheric attenuation versus Heavy Rainfall Rate, throughout the year of 2000. It is linearly proportional with 5dB/km.

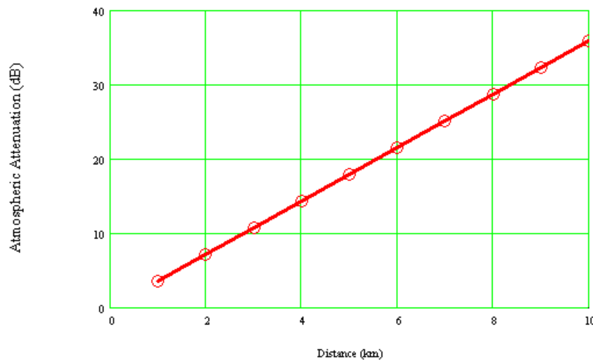

Figure 4: Atmospheric Attenuation as a function of Link Distance

Turbulence

Atmospheric turbulence produces temporary pockets of air with slightly different temperatures, different densities, and thus different indices of refraction. Laser beams experience three effects under turbulence. First, the beam can be deflected randomly through the changing refractive index cells, which is known as beam wander. Second, the phase front of the beam can vary, producing intensity fluctuations or scintillation (heat shimmer). Third, the beam can spread more than diffraction theory predicts. A good measure of turbulence is the refractive index structure coefficient, Cn^2 [21]. Because the air needs time to heat up, the turbulence is typically greatest in the afternoon ($Cn^2 = 10^{-13} m^{-2/3}$) and weakest an hour after sunrise or sunset ($Cn^2 = 10^{-17} m^{-2/3}$). Cn^2 is usually largest near the ground, decreasing with altitude. To minimize the effects of scintillation on the transmission path, FSO systems should not be installed close to hot surfaces. It is recommended to install a little bit higher above the rooftop (> 4 feet). The downtime due to scintillation can also be avoided through a large aperture receiver, widely spaced transmitters, finely tuned receive filtering, and automatic gain control [22]. From a trial-based study of free space optics systems in Singapore [23] which is tropical region and similar with Malaysian environment, the hourly average peak-to-peak scintillation levels as high as 5.5 dB during the hotter months. During the cooler months, average peak-to-peak scintillation did not exceed 3.5 dB. However, during a rain event, when the link suffers the most attenuation, is only about 2 dB. In this design, the large aperture receiver is used based on the commercial product and 2 dB is considered in the simulation.

Alignment

One of the key challenges with FSO systems is maintaining transceiver alignment. FSO transceivers transmit highly directional and narrow beams of light that must impinge upon the receive aperture of the transceiver at the opposite end of the link. Buildings are in fact, constantly in motion. This movement is the result of a variety of factors, including thermal expansion, wind sway, and vibration. Building sway is generally referred to as “base motion” [24]. Base motion can cause link outages in two ways: excess geometric loss (*GL*) due to pointing errors and large detector coupling loss due to tracking errors. *GL* occurs due to the spreading of the transmitted beam between the transmitter and the receiver. Typically, the beam spreads to a size larger than the receive aperture, and this “overfill” energy is lost. GL can be approximated with the following formula [22,24]:

$$GL(dB) = 10\log\left\{\frac{d_2}{d_1 + [R \times D]}\right\}^2 \tag{3}$$

where d_1 is the transmit aperture diameter (m), d_2 is the receive aperture diameter (m), R is the range (km), and D is the beam divergence (mrad).

Mispointing loss represents the imperfect alignment of the transmitter and the receiver results from the fact that most FSO systems transmit a beam with a Gaussian power distribution and that only a portion of the beam overlaps the receiver. Based on the commercial product the loss due to mispointing error is estimated to be 3 dB [22].

PROBABILITY OF ERROR

Error Rate for IM/DD

For OW with IM/DD technique, it is assumed that the channel is a zero-mean wide-sense stationary Gaussian process and that the receiver processing circuits, except for the threshold device, are linear. For the case of a linear-processing receiver circuit with a binary signal plus noise at the input, the sampled output is

$$r_0 = s_0 + n_0 \tag{4}$$

where n_o is a zero-mean Gaussian random variable, and s_o is a constant that depends on the signal being sent. That is

$$s_0 = \begin{cases} s_{01}, & \text{for a binary 1 sent} \\ s_{02}, & \text{for a binary 0 sent} \end{cases} \tag{5}$$

The general expression for the BER of any binary communication is [24]

$$P_e = P(s_1 sent)\int_{-\infty}^{V_T} f(r_0 \mid s_1)dr_0 + P(s_2 sent)\int_{V_T}^{\infty} f(r_0 \mid s_2)dr_0 \tag{6}$$

Thus, the two conditional PDFs are [25]

$$f(r_0 \mid s_1) = \frac{1}{\sqrt{2\pi}\sigma_0} e^{-(r_0 - s_{01})^2 / \left(2\sigma_0^2\right)} \tag{7}$$

$$f(r_0 \mid s_2) = \frac{1}{\sqrt{2\pi}\sigma_0} e^{-(r_0 - s_{02})^2 / (2\sigma_0^2)} \tag{8}$$

where σ_0^2 is the average power of the output noise from the receiver processing circuit where the output noise process is wide-sense stationary. From detection theory, the optimum detection threshold for maximum-likelihood is

$$V_T = \frac{s_{01} + s_{02}}{2} \tag{9}$$

Using equally likely source statistics for binary 1 and binary 2, it is readily shown that the BER for this binary case or unipolar signaling case, can be calculated as

$$P_e = Q\left(\frac{A}{2\sigma_0}\right) \tag{10}$$

where $Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} e^{-\lambda^2/2} d\lambda$ [25].

Error Rate for DCM/Diff.D

For DCM/Diff.D technique, the output signal, r_o is produced by subtracting the signal from Channel 1 (r_1) to Channel 2 (r_2) as shown in Figure 5.

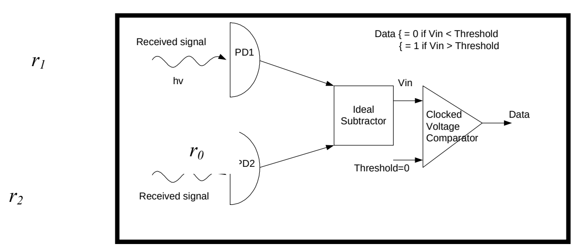

Figure.5: DCM/Diff.D technique

The derivation below is based on the assumption that an ideal subtractor is used in this design. Ideal subtractor means the subtractor without noise. r_1 and r_2 are the received signal after PD1 and PD2, whereas r_0 is the output signal after the subtraction. The received signal in channel 1 is

$$r_1 = s_1 + n_1 \tag{11}$$

and that of channel 2 is

$$r_2 = s_2 + n_2 = \overline{s_1} + n_2 \tag{12}$$

where $s_2 = \overline{s_1}$ which $\overline{s_1}$ means the complement of s_1. The output after subtraction is given as

$$r_0 = r_1 - r_2 = s_1 - \overline{s_1} + n_1 - n_2 = s + n \tag{13}$$

where $s = s_1 - \overline{s_1}$ and $n = n_1 - n_2$. The two channels are assumed to have equal length and n_1 and n_2 are independent, identically distributed (i.i.d.) Gaussian RV with zero mean and variance σ_0^2 and synchronization. In reality, synchronization is achieved when the frequency and phase between the reference signal (local oscillator) at the receiver in 'phase lock' with the received signal. One of the methods is phase-locked-loop. In this simulation, 2 PIN detectors are used and assumed with equal noise for 1 and 0 bit.

If this technique is assumed as synchronous reception:

$$s_1 = \begin{cases} 1 & \text{for a binary 1 sent} \\ 0 & \text{for a binary 0 sent} \end{cases} \tag{14}$$

$$s_2 = \begin{cases} 0 & \text{for a binary 1 sent} \\ 1 & \text{for a binary 0 sent} \end{cases} \tag{15}$$

Therefore,

$$s_o = \begin{cases} 1 & \text{for a binary 1 sent} \\ -1 & \text{for a binary 0 sent} \end{cases} \tag{16}$$

where $s_o = s_1 - s_2$

The received signal is polar signaling format which is also known as antipodal signal.

Since n_1 and n_2 are i.i.d. Gaussian RV with zero mean and variance σ_0^2, then n should be a Gaussian RV with zero mean and variance $2\sigma_0^2$ [26]. Thus, given s_1, r_0 is a Gaussian RV with mean A and variance $2\sigma_0^2$ and given s_2, r_0 is a Gaussian RV with mean $-A$ and variance $2\sigma_0^2$. Thus, the two conditional PDFs are

$$f(r_0 \mid s_1) = \frac{1}{2\sqrt{2\pi}\sigma_0} e^{-(r_0 - s_{01})/(4\sigma_0^2)} \tag{17}$$

$$f(r_0 \mid s_2) = \frac{1}{2\sqrt{2\pi}\sigma_0} e^{-(r_0 - s_{02})/(4\sigma_0^2)} \tag{18}$$

The optimum threshold for maximum likelihood detection is now

$$V_T = \frac{A - A}{2} = 0 \tag{19}$$

By considering equally likely *a priori statistics* probability, the BER can be easily calculated as

$$P_e = Q\left(\frac{A}{\sqrt{2}\sigma_0}\right) \tag{20}$$

Compared to (10), the signal amplitude is now reduced to $1/\sqrt{2}$ as that used for the unipolar system in order to have the same BER.

The boundary conditions for comparison between IM/DD and DCM/Diff.D is 100% of receiver power is focused on one PD with field of view (FOV) of *x* mrad for IM/DD whereas 50% of receiver power is focused on PD1 and PD2 with FOV of *x/2* mrad for DCM/Diff.D. A plot of the probability of bit error for IM/DD and DCM/Diff.D is shown in Figure 6 by considering a value of *A* is 0.1 *V* during voltage low and *A* is 2 *V* during voltage high. It is apparent that DCM/Diff.D has a 1.5 dB advantage over IM/DD since IM/DD requires a SNR that is 1.5 dB larger than that for DCM/Diff.D for the same probability of bit error at 1.10^{-12}.

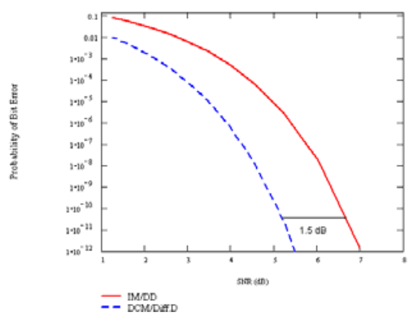

Figure 6: The probability of error in IM/DD and DCM/Diff.D

Figure 7 shows the voltage difference, V_d in IM/DD and DCM/Diff.D versus SNR. When the value of SNR is 6 dB, the value of V_d in IM/DD and DCM/Diff.D are 0.7 V and 1.55 V respectively. The V_d in IM/DD is about half of that in DCM/Diff.D. That means the threshold level in DCM/Diff.D is twice of IM/DD. By increasing a margin by several orders of magnitude, will result the stability of threshold level.

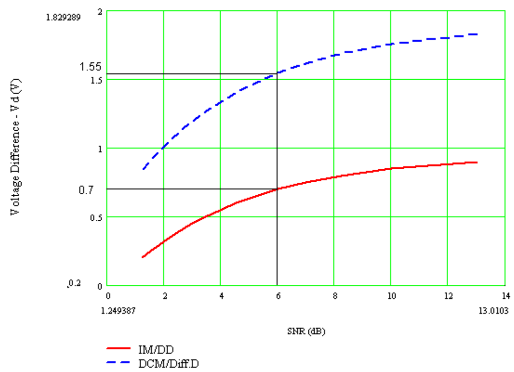

Figure 7: The voltage difference, V_d in IM/DD and DCM/Diff.D

RESULTS AND DISCUSSIONS

The study on BER performance is carried out against the transmission distance. Channel 1 and channel 2 are separated by 5 m from each other to avoid channel overlapping at the receiver. This is because the diameter of beam area is directly proportional to the link range and the beam divergence [22]. In this simulation, the beam divergence used is 1 mrad as it is better to avoid spreading of large beam and the maximum distance simulated is 4.5 km. The data rate used is 2.5 Gbps. Figure 8 shows the performance of the BER in relation to the transmission distance at STM-16 (2.5 Gbps) under the condition of heavy rain falling at the rate of 8.33×10^{-4} cm/sec. Assuming a BER threshold of 10^{-9}, the curve for conventional IM/DD shows a better BER at shorter distances of up to 1.5 km. At this distance, the received optical power is so low that the threshold voltage reaches its minimum and is masked by noise sources. However, it increases exponentially thereafter, and eventually flattens out as it is limited by the simulator's calculation. In contrast, the DCM/Diff.D performs outstandingly at distances ranging from 1 to 4 km. The DCM/Diff.D evidently has very small error increments and operates with limited noise. The differential concept described in Section 2 reduces the influence of the RIN at the optical receiver, yielding an improvement in sensitivity.

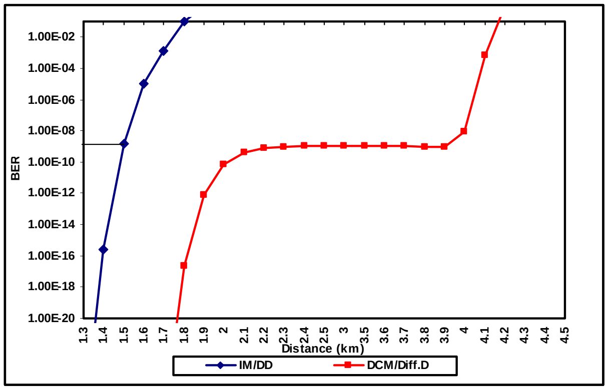

Figure 8: BER versus distance for DCM/Diff.D and IMDD at 2.5 Gbps Heavy Rainfall

CONCLUSIONS

The new transmission and detection scheme for FSO is proposed. This scheme is called DCM/Diff.D, utilizing amplitude subtraction to substitute the conventional dynamic threshold determination technique for bits regeneration. The longest distance for DCM/Diff.D at 2.5 Gbps was observed at 4 km while that the conventional IM/DD was 1.5 km only. Although DCM/Diff.D technique requires two channels (instead of only one in the conventional technique), the improvement provide is significant that it compensates the extra cost incurred. Therefore DCM/Diff.D could become a good alternative and great challenge for FSO systems in the near future.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to Mr.Azhar and all staff of Malaysian Meteorological Department, Petaling Jaya, Malaysia for their assistance in data collection.

REFERENCES

[1] T.H.Carbonneau and D.R.Wisely, (1998) “Opportunities and challenges for optical wireless the competitive advantage of free space telecommunications links in today’s crowded marketplace,” Wireless Technologies and Systems: Millimeter-Wave and Optical, Proc. SPIE, 3232: 119-128.

[2] M.M.Ebrahim and A.M.Ebrahim, (1996) “Performance analysis of optical receivers with space diversity reception,” IEE Proc. Commun., 143: 369-372.

[3] X.Zhu and J.M.Kahn, (2002) “Free-space optical communication through atmospheric turbulence channels,” IEEE Trans. Commun., 50: 1293-1300.

[4] A.Cartaxo, A.de Albuquerque, (1990) “Influence of the various types of noise on jitter performance in binary direct detection optical communication”, Proc. IEEE, 137: 375-378.

[5] Huang, S., Wang, L., (1996) “Exact Evaluation of Laser Linewidth Requirements for Optical PSK Homodyne Communication Systems with Balanced PLL Receivers”, Journal of Lightwave Technology, 14(5): 661-664.

[6] Jensen, N. G., Bodtker, E., Jacobsen, G., (1991) “Balanced Tuned Receiver Front End with Low Noise and High Common Mode Rejection Ratio”, Electronics Letters, 27(3): 234-235.

[7] Gustafson, E. K., Fejer, M. M, Byer, R. L., (1997) “Polarization-Based Balance Heterodyne Detection Method in A Sagnac Interferometer for Precision Phase Measurement”, Optics Letters, 22(17).

[8] Yamashita, S., Okoshi, T., (1994) “Suppression of Beat Noise from Optical Amplifiers Using Coherent Receivers”, Journal of Lightwave Technology, 12(6): 1029-1035.

[9] Swanson, E. A., Chan, V. W. S., (1986) Heterodyne Spatial Tracking System for Optical Space Communication, IEEE Transaction on Communications, 34(2): 118-126.

[10] Glance, B. S., Scaramucci, O., (1990) High-Performance Dense FDM Coherent Optical Network, IEEE Journal on Selected Areas in Communications, 8(6): 1043-1047.

[11] Smith, D. W., (1987) Techniques for Multigigabit Coherent Optical Transmission, Journal of Lightwave Technology, 5(10): 1466-1478.

[12] Arvizu, A., Mendieta, F. J., Chavez, R., (1998) Balanced Photoreceiver for Coherent Optical Communications, Instrumentation and Development, 3(10): 3-14.

[13] Abbas, G. L., Chan, V. W. S., Yee, T. K. (1985) A Dual-Detector Optical Heterodyne Receiver for Local Oscillator Noise Suppression, Journal of Lightwave Technology, 3(5): 1110-1122.

[14] Winzer, P. J., Chandrasekhar, S., Kim, H., (2003) Impact of Filtering on RZ-DPSK Reception, IEEE Photonics Technology Letters, 15(6): 840-842.

[15] Ferber, S., Ludwig, R., Boerner, C., Schubert, C., Langhorst, C. S., Kroh, M., Marembert, V., Weber, H. G., (2005) 160 Gbit/s DPSK Transmission Over 320 km Fibre Link with Long-Term Stability, Electronics Letters, 41(4).

[16] Ferber, S., (2003) Comparison of DPSK and OOK Modulation Format in 160 Gbit/s Transmission System, Electronic Letters, 39(20): 1458-1459.

[17] Lightpointe, Optical Wireless Solutions for Service Provider Applications, http://www.lightpointe.com. (Accessed on 13th May 2004).

[18] Ong, J.T., Timothy, K. I., Chong, J. H., Rao, S. V. B., (2003) Heavy Rain Effects on The Propagation of Free Space Optical Links in Singapore, Proceeding of Twelfth International Conference on Antennas and Propagation, 1: 365-368.

[19] Maha Achour , (2002) Simulating Atmospheric Free Space Optical Propagation: Rainfall Attenuation, Proc. SPIE on Free Space Laser Communication Technologies XIV , 4635: 192 - 201.

[20] Palais, J.C., (2004) *Fiber Optic Communications*, 4th Edition, Prentice Hall Int..

[21] Ghuman, B., Willebrand, H., (2002) *Making Free-Space Optics Work*.

[22] Isaac I.Kim, Ron Stieger, Joseph A.Koontz, Carter Moursund, Micah Barclay, Prasanna Adhikari, John Schuster and Eric Korevaar, (1998) Wireless optical transmission of fast Ethernet, FDDI, ATM, and ESCON protocol data using the Terralink laser communication system. Optical Engineering, 3143-3155.

[23] Nanyang Technology University, Network Technology Research Centre, Agilent Technologies, (2002) A Trial-Based Study of Free-Space Optics Systems in Singapore, produced for iDA Singapore.

[24] Scott Bloom, Eric Korevaar, John Schuster and Heinz Willebrand, (2003) Understanding the performance of free-space optics [Invited], Journal of Optical Networking, 2(6): 178-199.

[25] Cough, L. W., (2001) *Digital and Analog Communication Systems*, 6th Edition, Prentice Hall.

[26] Meyer, P. L., (1979) *Introductory Probability and Statistical Applications*, Addison-Wesley, Reading, MA.