Commun. Fac. Sci. Univ. Ank. Series A2-A3
V. 46. pp. 33-40 (2001)

WIRELESS OPTICAL LINKS : ATMOSPHERIC EFFECTS AND TRACKING ASPECTS

M. EFE, F. ÖZEK

Department of Electronics Eng., Fac.of Eng., Ankara University, Ankara, TURKEY

(Received Oct. 12, 2000; Revised Jan. 12, 2001; Accepted July 19, 2001)

ABSTRACT

Following the present day trend towards mobile communications, the possible use of medium power laser diodes in free space optical links between mobile on-sea terminals is evaluated. Considering the maximum communication distance as the ultimate measure of performance, the effects of the noise, bit rate, the atmospheric conditions from clear to hazy weather are analysed. The pointing error and tracking aspects are emphasized. Possible impulse noise due to the lightning is pointed out.

1.INTRODUCTION

Free space optical communication, FSOC, or wireless optical communication, being an application of optoelectronics, is quite a new alternative to the RF based systems [1] and has found successful indoor outdoor applications between fixed terminals [2] at the bit rates up to 50 Mbps [3]. In the long distance outdoor FSOC between the fixed, stationary terminals, naturally a narrow beam laser is to be used just as in any application of lasers in general. However, if the terminals are in motion, the line-of-sight requirement still being a must [4], the transmitter laser beam divergence has to be widened up to 35°. For simplicity, this paper only deals with FSOC between mobile on-sea terminals by night as the strong infrared emission of the Sun, by day, is very likely to hinder the system performance. However, a simple but effective method is suggested in [6] to reduce the effect of ambient light on such a system. Justification for the beam widening in such applications is the fact that the sailing ships are in three-dimensional motion, that is, both the terminal and receiver lurch along in their direction of movement so that the probability of detection would be almost nil if a narrow beam laser were employed. The widened laser beam can still be regarded directional which validates the advantage of confidentiality of FSOC, apart from the immunity to interference (the immunity issue will be addressed in proceeding sections). Moreover, when the terminals are in motion, accurately pointing the laser beam at the receiver hence tracking the transmitter become important issues.

2. MEDIUM POWER LASER DIODES

An investigation on the commercially available laser sources will indicate that the power outputs from 75 to 150 mW can typify the medium power laser diodes and the characteristics of which are given in Table 1, where θ// and θ⊥ are the parallel and perpendicular divergence angles of the elliptical laser beam, respectively

Table 1. Typical characteristics of medium power laser diodes

Power (mW)	λ(μ)	θ//(deg)	θ⊥(deg)
75	0.780	8	17
150	0.830	7	17

In order to maintain the far-field symmetry, i.e. θ// = θ⊥, which is 17 degrees, for on land applications the elliptical laser beam can be circularized, using an anamorphic prism pair (A.P.P.).

On the other hand, although the Gaussian profile of the laser diode output flattens out in the far-field, 86% of the power is to be taken into account [5], rather than the nominal power ratings of 75 and 150 mW.

3. RECEIVER STRUCTURE AND THE SIGNAL

One of the most common type of sensor, used in optical communication applications is the quadrant detector, in which four separate photodetectors are used to determine the instantaneous position error. Block diagram in Figure 1 shows the basic receiver components. After passing through a narrow band, laser line optical interference filter F, the signal carrying laser rays from the transmitter are collected and focused by a thin lens L onto the four-quadrant, 4Q, detector which both senses the laser signal and produces the data for tracking of the transmitter by the receiver and pointing its own laser beam towards the transmitter.

The collected laser signal does not form a fine point on the 4Q but an intentionally defocused spot so as to make tracking possible via ecartometry, meaning deviation measurement [6]. The voltage output of each quadrant is proportional to its share of the of laser energy contained in the spot.

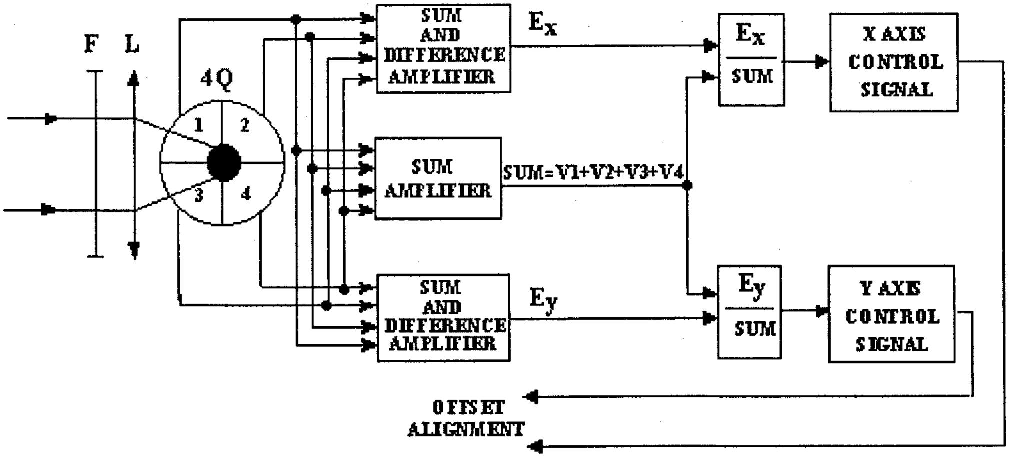

Figure 1. Basic receiver sensor structure and 4Q output for signal detection and tracking.

The horizontal E_x and vertical E_y transmitter position deviations from the detector (also called "error signals") axis can be calculated from Eq.(1) and (2).

$$E_x = (V_2 + V_4) - (V_1 + V_3) \quad (1)$$
$$E_y = (V_1 + V_2) - (V_3 + V_4) \quad (2)$$

If the transmitter is on the detector (receiver) axis, then each quadrant will receive equal laser energies, i.e. $E_x = E_y = 0$. The laser power signal S at the 4Q is given in Eq.(3).

$$S = \frac{P \exp[-\tau R]\, F\%\, S(opt)}{\pi R^2 \tan^2 \theta / 2} \text{ Watts} \quad (3)$$

where P: laser diode power, τ: atmospheric attenuation coefficient, R: transmitter to receiver distance, F%: optical filter peak transmission, S(opt): lens area and $\theta = \theta\perp$: circularized laser beam angle. In the numerical evaluations the following data are used: F% = 50 for the average laser wavelength $\lambda(av) = 0.8\ \mu$, $S(opt) = 4.9\ cm^2$ for a D = 2.5 cm dia and f = 2.47 cm lens. For the laser spot size of a = 2.8 mm in dia, the lens plus A = 11.3 mm dia 4Q combination results in the receiver field-of-view of FOV = 20° which is almost equal to $\theta = 17°$. The atmospheric attenuation coefficient is $\tau = 2.0 \times 10^{-4}\ m^{-1}$ at $\lambda(av) = 0.8\ \mu$ for clear weather at sea level [7], considering again the on-sea applications.

4. NOISE

By night, the only source of noise might be earth self emission (GSE) of infrared. The amount of GSE can be assessed using the well-known Planck's equation [7] which is re-written for per steradian, sr, and the emission within the bandwidth $\Delta\lambda$ of the optical filter in Eq.(4).

$$L(GSE) = \Delta\lambda(1.19 \times 10^4)\lambda^{-5}/(\exp[14388/\lambda T]-1) \quad W/cm^2.sr \tag{4}$$

where $\Delta\lambda$ = 10 nm, λ = 0.8 μ and T = 300° K. From Eq.(4), the irradiance due to earth is L(GSE) = 3.3×10^{-24} W/cm^2.sr. The corresponding background current I(GSE) is than found to be, Eq.(5), $\cong 4 \times 10^{-25}$ A, which is well below the 4Q dark current I(d) = 50 nA,max.

$$I(GSE) = L(GSE)\ \Omega(4Q)\ F\%\ S(opt)\ \sigma \tag{5}$$

where $\Omega(4Q)$: 4Q solid angle, sr = $2\pi(1-\cos FOV/2)$ and σ: 4Q responsivity = 0.5 A/W. Therefore, the shot noise oriented 4Q noise equivalent power NEP = 2.2×10^{-13} W/Hz$^{1/2}$ is the only noise to be considered where Hz indicates the detection bandwidth BW. In the computations, the BW is varied between 1.2 and 57.6 kHz, corresponding to the communication bit rates from 2.4 to 115.2 kbps.

5. SIGNAL-TO-NOISE RATIO (SNR)

The Infrared Data Association IrDA specification states that the bit error rate BER shall be no greater than 10^{-8} [8]. In this work the BER is set to 10^{-9} which yields a threshold SNR of 72 (18.67 dB), by the Eq.(6) when the frequency shift keying is used in communication,

$$BER = Q\ (SNR/2)^{1/2} \tag{6}$$

where Q is the Gaussian Q function which is 6 for the BER of 10^{-9}, [9].

6. LASER BEAM POINTING AND TRACKING

In an optical communication application if the physical channel is unguided - such as free space- the optical system usually has a very narrow transmit/receive beamwidth in order to fully realise its performance potential. Therefore, spatial pointing and tracking become important issues in the design of such systems. Depending on the type and direction of the communication, optical tracking systems can be employed either at the receiving and/or the transmitting end of the optical link. The main purpose of the optical pointing and tracking system, as shown in Figure 1, is to keep the incoming beam properly centered in the 4Q detector plane in spite of beam wander and/or relative motion between the transmitter and receiver. An optical sensor is used to generate the error-control from the received optical beam. Any offset from the centre of the 4Q detector (Fig 1) produces a control error voltage, i.e., E_x and\or E_y as given in section 3, in the axis in which it occurred, creating a drive voltage to the actuator used that will position the lser beam back to the null position.

Beam tracking can be carried out either at one of the terminals or at both terminals according to the communication requirements and the application. If the beam tracking is attempted at only one of the terminals then it is called single ended beam tracking[10]. In single ended beam tracking, the receiver establishes a line of sight by tracking the arriving optical beam from the transmitter that is pointed towards the receiver and is utilized when only one way communication is needed. On the other hand, when two way communication is needed, i.e., when the two terminals both transmit and receive, tracking is needed at either terminals thus, the technique so called double ended beam tracking is used. However, when double ended beam tracking is employed, pointing errors can develop at both ends of the link and the pointing accuracy at one end affects the errors at the other end. The pointing errors at both ends, therefore, evolve as joint variables that are statistically related. In order to reduce the complexity and the level of errors, a tracking system that switches between single ended and double ended tracking systems according to the requirement of the communication link could be used. However, additional measures must be taken to ensure the communication continuity when switching is utilized. Thus, a scheme must be developed that will prevent any kind of decision that will result in the stopped beam tracking action, hence the communication break down, at both terminals at the same time. To the authors' knowledge, such a system has not yet been reported in the literature, but a successful switching action might prove practically very beneficial.

7. RESULTS AND DISCUSSION

Figure 2 shows the variation of the maximum estimated communication distance R_{max} with the bit rate. At 57.6 kbps, i.e. speech communication, R_{max} varies between 300 to 400m for $P = 75$ to 150 mW, respectively, which are practically useful distances for closely sailing ships. At the lower bit rates, R_{max} is about half a kilometer and longer.

Table 2 summarizes the effect of various atmospheric conditions on R_{max} at 57.6 kbps. Compared to the clear weather, R_{max} is about 30 to 40m shorter for the hazy conditions.

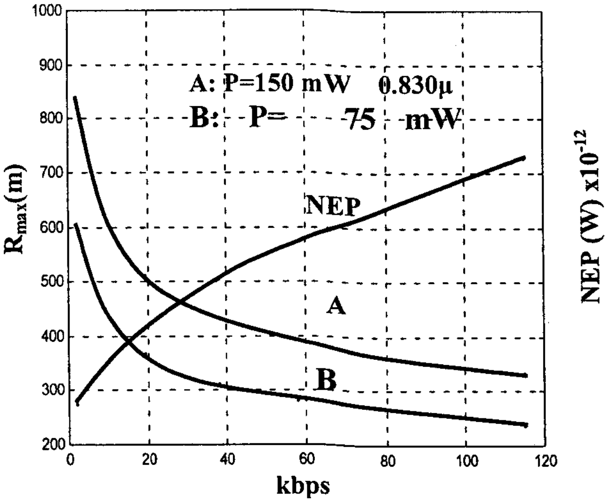

Figure 2. Variation of maximum estimated communication distance with bit rate for clear weather (NEP: Noise Equivalent Power)

The attenuation constants given in Table 2 are the values calculated at sea level [7]. Estimated range values given in Figure 2 and Table 2 correspond to the SNR of 72 (18.76 dB) where N is the dark current, I(d), based NEP. However, when the detector load resistance thermal noise, $i(R_L)$, Eq.(7), is also considered and added to the detector noise $i(d) = \sqrt{2eI(d)\Delta f}$, where, e = 1.6 x 10^{-19} Coulomb, the resulting total noise current will be $i(n) = \sqrt{i^2(d) + i^2(R_L)}$ which is then converted to N, by using σ = 0.5 A/W, for a given Δf. Increase in the N results in the shorter R_{max} values. For R_L = 200 kΩ[1] and clear atmospheric conditions R_{max} varies between 240 m and half a kilometer, for 57.6 and 2.4 kbps, respectively.

$$i(R_L) = \sqrt{4kT\Delta f / R_L} \qquad (7)$$

where k = Boltzmann constant = 1.38 x 10^{-23} J/°K
T = 293°K (20°C)
R_L= load resistance, Ω

---

[1] The selection of the value of R_L is a compromise between having a low detector noise and a high cut-off frequency. A high value of R_L reduces the detector noise, however it also reduces the cut-off frequency along with it.

Table 2. Effect of various atmospheric conditions on R_{max} at 57.6 kbps, (τ values from Ref.6)

Atmospheric Condition	τ (m^{-1}) x10^{-4}	R_{max}(m) 75 mW	R_{max}(m) 150 mW
Clear	2.0	282	394
Light haze	4.0	275	379
Medium haze	6.0	269	368
Haze	10.0	256	346

It can be found in the literature that [11] one of the strong near infrared emissions from the lightning occurs at 0.777μ which causes an irradiance of about 1.85 x 10^7 J/nm.m^2 measured in 50 ms. Corresponding to approximately 0.4 nW/cm^2 on the ground, this irradiance level may induce, especially when the multiple lightning strikes occur, if a 0.780 μ laser diode at the transmitter and a $\Delta\lambda$ = 10 nm optical filter at the receiver are employed. For example at R_{max}= 280 m and 57.6 kbps, the laser intensity on the receiver is 1.1 nW/cm^2, which is quite comparable to the lightning intensity.

Although one drawback of the laser beam widening may be the risk of "eavesdropping" of the transmitted signal by an unintended receiver, such a risk can be minimised by using special "coding" techniques to maintain the communication confidentiality. On the other hand, it does have an advantage as it reduces the effect of scintillation on the laser beam. Scintillation due to turbulance may be important for a pencil beam laser, however, for a wide angle beam the probability of the signal strength getting degraded is negligible.

As mentioned before, for simplicity the paper has addressed the optical communication problem at night conditions only. Obviously, the presence of Sun light aggravates the problems that have already been mentioned and imposes major restrictions on communication. For instance the communication distance gets significantly reduced if the optical communication is attempted in day light. As an example, the maximum range for speech communication is not longer than a hundred meters for applications by day [12].

To conclude, a feasibility study on wireless optical mobile communication has been presented in this work. Although optical communication between fixed terminals has already been realised and commercialised, wireless optical mobile communication is a new and promising area of application. The paper gives a compact presentation of the requirements of an optical mobile communication system by explaining the elements and stages of such a system in general and also analysing possible application aspects with emphasis on atmospheric effects, and tracking.

REFERENCES

[1] PAHLAVAN, K. and, LEVESQUE, A.H.: Wireless Information Networks. pp 417-441, Wiley 1995

[2] http:\\www.cablefree.co.uk, http:\\eagleoptic.com/indexno.html

[3] MARSH, G.W. and KAHN, J.M.: 50-Mb/s diffuse infrared free-space link using on-off keying with decision-feedback equalization. IEEE Photon. Tech.Letts., 6 (1994) 1268.

[4] Data transmission with IR beams attains 125 Mb/s. Photon. Spectra, July (1993) 16

[5] OZEK, F. and EFE, M.: Reduction of ambient light effect on ecartometry for a laser illuminated turget. Measurement Science and Technology, 9 (1998) 1638-1640.

[6] SALEH, M.B.A. and TEICH, M.C.: Fundamentals of Photonics. Wiley (1991) 85.

[7] MOLLIE, P. and CHABANNES, F.: Principe et realization des systemes laser en aeronautique. NATO-Advisory Group for Aerospace Research and Development (AGARD), Lecture Series on Opto-Electronics, LS-71 (1974) p.8-1.

[8] HUDSON, R.D: Infrared System Engineering. Wiley (1969) 35

[9] http://www.irda.org

[10] GAGLIARDI, R.M. and KARP, S.: Optical Communications: Wiley, New York (1995) 42

[11] ORVILLE, R.E. and HENDERSON, R.W.: Absolute Spectral Irradiance Measurements of Lightning from 375 to 880 nm; Journal of Atmospheric Sciences. E. Vol 41 (1984) 3180

[12] OZEK, F.: Estimation of the range for free space optical links between mobile terminals; Journal of Technical Physics (Polish Academy of Sciences). Vol 41 No 4 (2000) 429.