BER and Outage Probability of DPSK Subcarrier Intensity Modulated Free Space Optics in Fully Developed Speckle

Wasiu O. Popoola
Northumbria Communication Research Lab (NCRLab), Northumbria University, Newcastle upon Tyne, UK.
Email: wasiu.popoola@unn.ac.uk

Zabih Ghassemlooy and Erich Leitgeb*
Northumbria Communication Research Lab (NCRLab), Northumbria University, Newcastle upon Tyne, UK.
*Institute of Broadband Communications, Graz University of Technology, Graz, Austria.
Email: fary.ghassemlooy@unn.ac.uk and erich.leitgeb@tugraz.at

***Abstract*--In this paper a differential phase shift keying (DPSK) subcarrier intensity modulated (SIM) free space optical (FSO) link is considered in negative exponential atmospheric turbulence environment. To mitigate the scintillation effect, the selection combining spatial diversity scheme (SelC) is employed at the receiver. Bit error rate (BER) and outage probability (P_{out}) analysis are presented with and without the SelC spatial diversity. It is shown that at a BER of 10^{-6}, a maximum diversity gain 25 dB is predicted. And about 60 dBm signal power is required to achieve an outage probability of 10^{-6}, based on a threshold BER of 10^{-4}.**

Index Terms—Free-space optics, DPSK, turbulence, spatial diversity, negative exponential distribution, outage probability.

I. INTRODUCTION

In today's access network, the FSO technology is playing an increasing complementary role to the radio frequency (RF) based techniques. This is attributable to its fundamental feature of huge bandwidth that is comparable to that obtainable from optical fibre but with an added advantage of lower deployment cost and time [1]. In recent years we have seen a steadily growing research interest in FSO systems accompanied by successful field trials that is now culminating into commercial deployments [1-4]. The earlier scepticism about FSO's efficacy, its dwindling acceptability by service providers and slow market penetration are now rapidly fading away, judging by the number of service providers, organisation, government and private establishments that now incorporate FSO links into their network infrastructure [5, 6].

Of course, terrestrial FSO links are not free of challenges; the atmospheric constituents (gases, aerosol, rain, fog, and smoke) extinguish and scatter photons traversing the atmosphere. The most deleterious being the thick fog, which could result in up to 270 dB/km attenuation coefficient [1]. This potentially limits the achievable link range to less than 500 m during such condition [7]. In clear atmospheric conditions, longer link ranges are feasible. However, due to atmospheric turbulence effects, small but random changes occur in the atmospheric temperature. This by extension, results in random changes in the atmospheric index of refraction along the path of the optical radiation. This metamorphoses into random phase and irradiance fluctuations (scintillation) of the optical radiation at the photodetector. Detailed study of the atmospheric turbulence can be found in [8-10]. The scintillation effect can be likened to the random fading effect on radio communication caused by the multipath propagation/channel frequency selectivity. Channel fading just like in RF communications, can cause severe degradation in the performance of an FSO link if unmitigated.

Selecting the most appropriate modulation scheme for a communication system is important factor which determines the overall system performance and cost. The requirement would be to have a low BER at low SNR and perform well in dispersive environment. In terrestrial FSO links; the simple and widely adopted on-off keying (OOK) [11] signalling format requires adaptive threshold to perform optimally in a fading environments. This poses a serious design difficulty that can be circumvented by employing the SIM scheme [12]. And for the full and seamless integration of FSO into existing networks the study of SIM becomes compelling because existing networks already contain subcarrier signals.

In weak turbulence modelled using the tractable log normal distribution, the spatial diversity has been studied to mitigate turbulence induced irradiance fading [11-13]. Likewise, FSO employing various forward error control techniques have been reported in literature [14-18] with varying degrees of gains and complexity. In this paper, a DPSK pre-modulated SIM terrestrial FSO link is presented with the selection combining spatial diversity adopted to ameliorate the scintillation effect. DPSK offers the advantage of adopting a no-coherent detection at the receiver end, thus avoiding the use of more

This paper was partly presented during the CSNDSP 2008 in Graz, Austria.

complex synchronization circuitry. In addition to mitigating scintillation without introducing additional latency into the system, spatial diversity also helps to prevent temporary outage/blocking due to birds or other small flying object cross the propagation path; it is also simpler to implement and very cost effective compared to the adaptive optics.

The rest of the paper is organised as follow: in Section II we describe the proposed DPSK-SIM, while the system performance analysis with and without the SelC spatial diversity is detailed in Section III. In Section IV, numerical simulation results are presented and discussed. The concluding remarks are then presented in Section V.

II. DPSK SUBCARRIER INTENSITY MODULATION

A. System description

In SIM, the data of symbol rate R_b is first pre-modulated on to a RF signal of frequency ω_c. The modulated subcarrier RF signal is then used to directly modulate the irradiance of an optical carrier which can either be a light-emitting-diode (LED) or a laser diode. The subcarrier modulated signal is DC-level shifted prior to modulating the optical source to ensure that the driving current of the laser diode is not less than its threshold current.

After traversing the atmospheric channel, the receive telescope coated with an optical band pass filter to limit the background radiation focuses the received irradiance onto the direct detection PIN photodetector, which is followed by a trans-impedance amplifier (TIA). The electrical band pass filter (BPF) with a centre frequency ω_c and bandwidth $2R_b$ allows the SIM signal through, and removes any DC component present. Finally, a standard DSPK demodulator is then used to recover the transmitted data as shown in Fig. 1.

Here we have assumed that the carrier and the local oscillators are both of the same frequency. The sampler output is delayed by one bit and is compared with the next signal received. The difference in the phase of the two sampled signals y_k and y_{k-1} determines the binary logic level of the received data.

The SIM leverages on the availability of stable RF oscillators and filters, hence any of the evolved digital modulation techniques such as PSK, frequency shift keying and quadrature amplitude modulation can in principle be used. In this work however, a binary differential DPSK is adopted in order to circumvent the absolute phase estimation (and its accompanying ambiguity) requirement of the coherent demodulated PSK [19]. The fact that the atmospheric turbulence channel can be rightly assumed to be 'frozen' for more than two consecutive data symbols makes the implementation of the DPSK decoder at the receiver feasible. The 'frozen' channel assumption is premised on the turbulence correlation time, which is known be on the order of a hundreds of millisecond [11, 20]. The instantaneous photocurrent $i_r(t)$ can now be modelled as [21]:

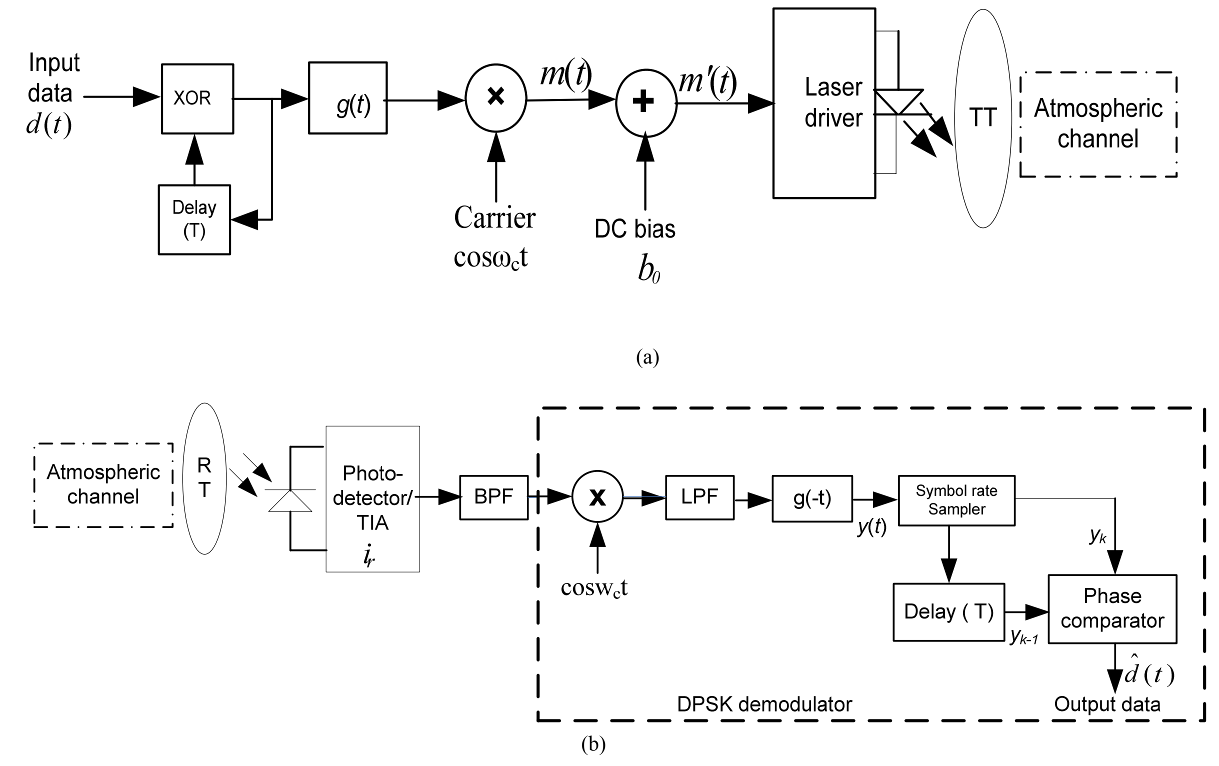

Fig. 1: A schematic system block diagram of an FSO link employing DPSK modulated SIM; (a) transmitter and (b) receiver. TIP-trans-impedance amplifier; TT-Transmit telescope; RT-Receive telescope; *T*-Symbol duration.

$$i_r(t) = RI(1+\beta m(t)) + n(t), \quad (1)$$

where $I = I_{peak}/2$, I_{peak} is the peak received irradiance, R is the photodetector responsivity, β is the modulation index and $m(t) = d(t)g(t)A_c\cos[\omega_c t + \theta]$ is the subcarrier signal of peak amplitude A_c; $d(t)$ is the input signal, $g(t)$ represents the rectangular pulse shape function and the additive noise $n(t) \sim N(0,\sigma^2)$ is assumed to be white Gaussian.

The condition $|\beta m(t) \leq 1|$ must always be fulfilled for the continuous wave optical transmitter to operate within its dynamic range. This places an upper bound on the amplitude of the subcarrier for a given value of β. With the subcarrier pre-modulated using DPSK and normalising β to unity, the peak amplitude $A_c \leq 1$.

B. Noise sources

Background noise: This is due to radiations from both the sky and the sun, with their irradiance (power per unit area) given, respectively as [22-24]:

$$I_{sky} = N(\lambda)\Delta\lambda\pi\, \Omega^2/4\,, \quad (2)$$

$$I_{sun} = W(\lambda)\Delta\lambda\,, \quad (3)$$

where $N(\lambda)$ and $W(\lambda)$ are the spectral radiance of the sky and spectral radiant emittance of the sun, respectively, $\Delta\lambda$ is the bandwidth of the optical band pass filter at the receiver, and Ω is the receiver field of view angle (FOV) in radian. By carefully choosing a receiver with a very narrow FOV and $\Delta\lambda$, the impact of background noise can be greatly reduced. Optical BPF in the form of coatings on the receiver optics/telescope with $\Delta\lambda < 1$ nm are now readily available. Empirical values of $N(\lambda)$ and $W(\lambda)$ under different observation conditions are also available in literature [21-23]. The background noise is a shot noise with a variance given by [23]:

$$\sigma^2_{Bg} = 2qBR\,(I_{sky} + I_{sun})\,, \quad (4)$$

where B is the system electrical bandwidth. That is the bandwidth of the LPF shown in Fig. 1(b).

Thermal noise: This is caused by the thermal fluctuations of electrons in the receiver circuit of equivalent resistance R_L and temperature T_e. Its variance is given by:

$$\sigma^2_{Th} = 4kT_e BR_L^{-1} \quad (5)$$

Noise due to the quantum nature of light, the dark current and the relative intensity noise are assumed too small to be reckoned with. Hence, the total noise variance is given as:

$$\sigma^2 = \sigma^2_{Bg} + \sigma^2_{Th}\,. \quad (6)$$

From (1) and (6), the electrical signal-to-noise ratio (SNR_e) can thus be derived as:

$$SNR_e = A_c^{\,2}R^2I^2/2\sigma^2\,. \quad (7)$$

The work presented in this paper is for a single subcarrier, however more than one subcarrier could be adopted to modulate the optical carrier irradiance.

C. Atmospheric turbulence

For FSO links spanning over 1 km, turbulence induced multiple scatterings do take place and the log normal turbulence model [9] characterised by single scattering event clearly becomes invalid. The strength of irradiance fading encountered in atmospheric turbulence is often referred to as the scintillation index defined as: $S.I = E[I^2] - E[I]^2/E[I]^2$; which is the normalised log irradiance variance. For links covering over 3 km, the turbulence effect can easily tend towards saturation; in which the *S.I.* begins to decrease due to multiple scattering and it then settles at a value of unity [8, 9]. This describes the fully developed speckle regime. In this regime, the optical radiation field fluctuation obeys the Rayleigh distribution [9] and that means that the irradiance fluctuation will follow negative exponential statistics as given by (8). The validity of the negative exponential irradiance fluctuation is widely acknowledged in literature and has also been experimentally verified [8]. Other turbulence models notably the log-normal-Rician [25], the *I-K* [26] and the gamma-gamma [10] all reduce to the negative exponential distribution in the limit of strong turbulence as given below:

$$p(I) = I_o^{-1}\exp(-I/I_o), \qquad I_o > 0 \quad (8)$$

where $E[I] = I_o$ is the mean received irradiance. For analogue SIM systems such as cable television signal transmission over optical fibre links, the average SNR suffices as a performance indicator but not for the digital SIM systems. Hence, in the next section the BER and the outage performance metrics suitable for digital communications in fading channel are presented.

D. Selection combining (SelC) spatial diversity

For fading channels such as the atmospheric turbulence channel, higher transmitted optical power is required to maintain the link performance level. However, increased power level is an undesirable constraint for a number of reasons including, safety and cost. Hence, there is a need to mitigate this deleterious atmospheric turbulence induced fading (scintillation) effect. Suitable candidates for doing this include: forward error control, adaptive optics, and spatial/time diversity schemes. Here, the spatial diversity technique employing an array of N-PIN photodetectors is considered.

Since at the subcarrier level the data is encoded using DPSK - a technique that requires no absolute phase extraction for its demodulation - then the spatial diversity adopted must not require absolute phase extraction as well. Hence, the choice of SelC spatial diversity in this work. In this diversity scheme, the photodetector with the highest SNR is selected out of all the N identical photodetectors. The selected branch is also the pupil with the highest received irradiance since all the paths will experience similar noise levels.

For fair comparison with a single photodetector case, each receiver aperture is made equal to A_p/N, where A_p is the receiver aperture for a single receiver system. Without any loss of generality, A_p is normalised to unity. In order for the signal received by the photodetectors to be uncorrelated, the spacing s between any two photodetectors must not be less than the atmospheric turbulence correlation distance ρ_o; a value which only measures a few centimetres [13].

III. PERFORMANCE METRIC ANALYSIS

A. Bit-error-rate (BER)

The generic performance metric of a digital communication system is the BER and for a DPSK based SIM-FSO link; this metric, conditioned on the received irradiance is given by [27]:

$$P_{ec} = 0.5\exp(-0.5 SNR_e) \quad . \tag{9}$$

However, in the face of scintillation the unconditional BER given by (9) is averaged over the irradiance fluctuation statistics (8) to obtain the following unconditional BER.

$$\begin{aligned} BER &= \int_0^\infty P_{ec}\, p(I)\, dI \\ &= \frac{1}{2I_o}\int_0^\infty \exp\left[-\frac{I}{I_o} - \frac{1}{4}\left(\frac{A_c R I}{\sigma}\right)^2\right] dI \end{aligned} \tag{10}$$

The above expression can be conveniently simplified by invoking equation (3.322.2) in [28] to obtain:

$$\begin{aligned} BER &= \sqrt{\pi / SNR}\, \exp(SNR^{-1}) \times \\ & Q\left(\sqrt{\pi / SNR}\right) \end{aligned} , \tag{11}$$

where the subcarrier amplitude A_c has been normalised to unity and $SNR = R^2 E[I]^2/\sigma^2$.

However, with the SelC spatial diversity, the SNR_e can be easily derived as:

$$SNR_{e-SelC} = \frac{R^2 A_c^2 I^2}{2N(N\sigma_{Th}^2 + \sigma_{Bg}^2)} . \tag{12}$$

It should be noted that, the background noise is proportional to the receiver aperture area while the thermal noise is not. Hence, the unconditional BER with SelC is obtainable from:

$$BER_{SelC} = \int_0^\infty P_{ec}\, p(I_{\max})\, dI , \tag{13}$$

where $P_{ec} = 0.5\exp(-0.5 SNR_{e-Sel})$ and $I_{\max} = \max\{I_i\}_{i=1}^N$ is the strongest of all received irradiance from all the N-PIN photodetectors. The probability density function (pdf) of I_{max}, given by $p(I_{\max}) = p(\max\{I_i\}_{i=1}^N)$ is obtained first by finding the cumulative distribution function of I_{max} at an arbitrary point and then differentiating. The resulting pdf is given by (14) and the detailed proof is presented in Appendix A.

$$p(I_{max}) = \tfrac{N}{I_o}\exp(-I/I_o)(1-\exp(-I/I_o))^{N-1} . \tag{14}$$

The plot of the pdf of I_{max} is shown in Fig. 2 for different values of N and $E[I] = I_o = 1$.

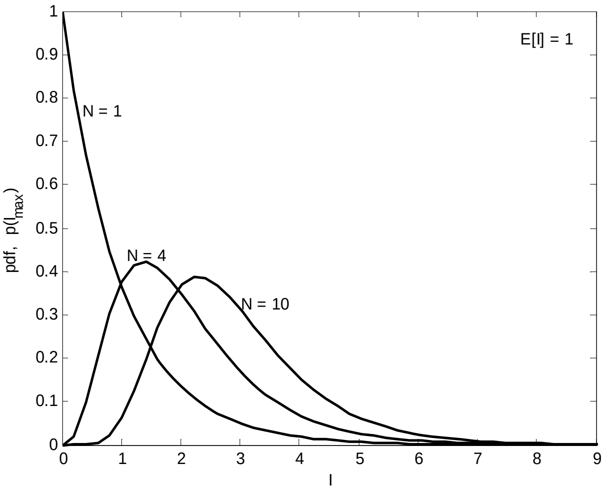

Fig. 2: The pdf $p(I_{max}) = p(max\{I_i\}_{i=1}^N)$ for N = 1, 4 and 10, and $E[I] = I_o = 1$

With the SelC spatial diversity the BER is given by:

$$BER_{SelC} = \int_0^\infty \frac{N}{2I_o}\left(1-\exp(-I/I_o)\right)^{N-1} \exp\left(\frac{-I}{I_o} - \frac{R^2 A^2 I^2}{2N(\sigma_{Bg}^2 + N\sigma_{Th}^2)}\right) dI . \tag{15}$$

This expression (15), to the best our knowledge has no closed form. As such, it can only be evaluated via numerical methods.

B. *Outage probability P_{out}*

The FSO system performance with respect to the generic average BER metric is the most reported metric; however, a system with an adequate average BER can temporarily suffer from an increase in error rate due to deep fades and this 'short outage' is not adequately modelled by the average BER [29]. An alternative performance metric commonly used in fading channels is the outage probability. It is defined as the probability that the BER is greater than a threshold level BER^*. This is akin to finding the probability that the SNR that results in BER is lower than a threshold level SNR^* that corresponds to the BER^*. That is:

$$P_{out} = P(BER > BER^*) \equiv P(SNR < SNR^*)\,, \quad (16)$$

where $SNR^* = (RAI^*)^2/2\sigma^2$, and I^* which can be obtained from the solution of (10) is the receiver sensitivity required to attain BER^*.

Combining (7) and (8), it is obtained that the received irradiance I_o needed to attain an outage probability P_{out} is:

$$I_o = \frac{I^*}{\ln(1-P_{out})^{-1}}\,. \quad (17)$$

With SelC, the outage probability is the cumulative density function of I_{max} whose pdf is plotted in Fig. 2. Thus, combining (7), (12), (14) and (A3) of Appendix A, the received irradiance $I_{o\text{-}Selc}$ needed to attain a given P_{out} is derived as:

$$I_{oSelC} = \frac{I^*}{\ln\left(1-\sqrt[N]{P_{out}}\right)^{-1}}\left(\frac{N(N\sigma^2_{Th}+\sigma^2_{Bg})}{\sigma^2_{Th}+\sigma^2_{Bg}}\right)^{0.5}. \quad (18)$$

From the foregoing, the diversity gain I_o/I_{oSelC} can thus be obtained.

IV. NUMERICAL RESULTS AND DISCUSSIONS

The numerical simulations presented in this section are based on the parameters of Table I. In Fig. 3, we show the BER obtained from (11) and (15) against the receiver sensitivity with and without SelC. This plot brings to bare the potential gain of SelC in reducing the required sensitivity for a given BER. For example, to achieve a BER of 10^{-6} with no diversity, about 23 dBm of received irradiance is required while with two photodetectors (N = 2), about -1.7 dBm is needed to achieve the same level of performance. Moverover, as the number of photodetectors increases, the attained diversity gain per additional detector reduces. For instance, for N = 2, the gain per detector at a BER of 10^{-6} is ~12 dB and this reduces to about 5 and 4 dB for N = 8 and 10, respectively. This result is summarised in Table II for up to 10 photodetectors.

To consider the outage probability, equations 17 and 18 are used. In Fig. 4, we plotted the P_{out} against I_{oSelC} with I^* = 0 dBm, being the sensitivity value required to attain a BER of 10^{-4} according to Fig. 3(a). This graph shows that for a threshold BER of 10^{-4}, achieving a DSPK-SIM with an outage probability of 10^{-6} or better, will require a minimum of 60 dBm received irradiance without SelC. This requirement reduces to ~35 dBm and ~23 dBm, respectively with 2 and 4 photodetectors. The inference from Fig. 4 is therefore similar to that of Fig. 3(b). To further illustrate the gain of using SelC in the saturation regime, we show in Figs. 5 and 6 the predicted diversity gain at different values of P_{out} and N. With 2 photodetectors and an outage probability of 10^{-6}, the

Table I: Numerical simulation parameters

Parameter	Value
Symbol rate R_b	155 Mbps
Spectral radiance of the sky $N(\lambda)$	10^{-3} W/cm$^2\mu$mSr
Spectral radiant emittance of the sun $W(\lambda)$	0.055 W/cm$^2\mu$m
Optical band-pass filter bandwidth $\Delta\lambda$ @ λ = 850 nm	1 nm
PIN photodetector field of view FOV	0.6 rad
Radiation wavelength λ	850 nm
Number of Photodetectors N	$1 \le N \le 10$
Load resistance R_L	50 Ω
PIN photodetector responsivity R	1
Operating temperature T_e	300 K
Electrical low-pass filter bandwidth	155 MHz

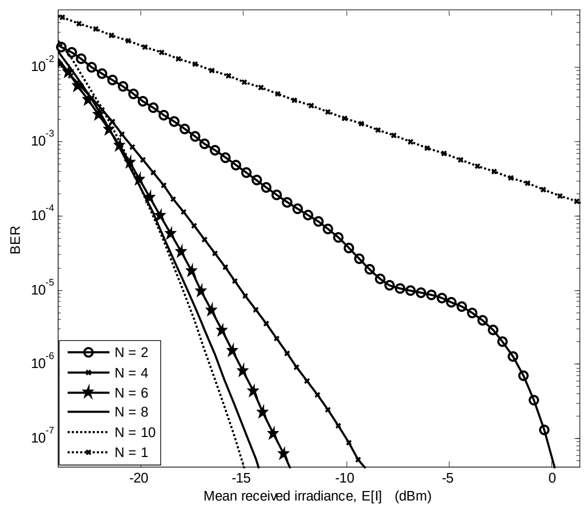

Fig. 3: The graph of BER against the receiver sensitivity in saturation turbulence regime for N = [2, 4, 6, 10]

Table II: Gain per photodetector at a BER of 10^{-6}

N	1	2	4	6	8	10
Sensitivity (dBm)	23.1	-1.7	-12.5	-15.2	-16.2	-16.7
Gain (dB) per N	0	12.4	8.9	6.4	4.9	4.0

maximum predicted gain per detector is about 14 dB as depicted in Fig. 5. This predicted gain is observed to be even higher at lower values of P_{out}. This makes sense as the use of diversity in a fading channel increases the received signal strength and by extension a lower P_{out}. And in Fig. 6, it is clearly shown that the gain (dB) per detector peaks at $N = 2$ and then decreases thereafter.

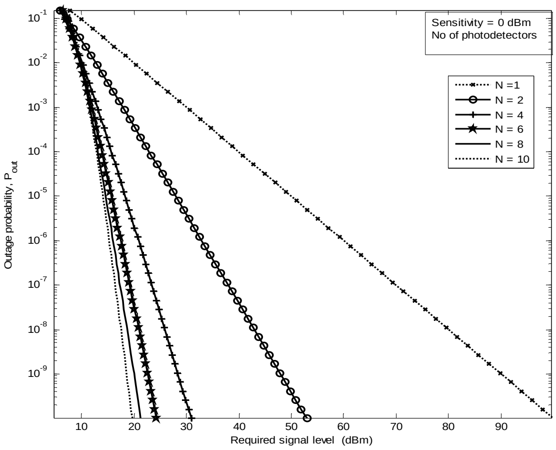

Fig. 4: Outage probability against the received irradiance with $I^* = 0$ dBm for $N = [1, 2, 4, 6, 10]$.

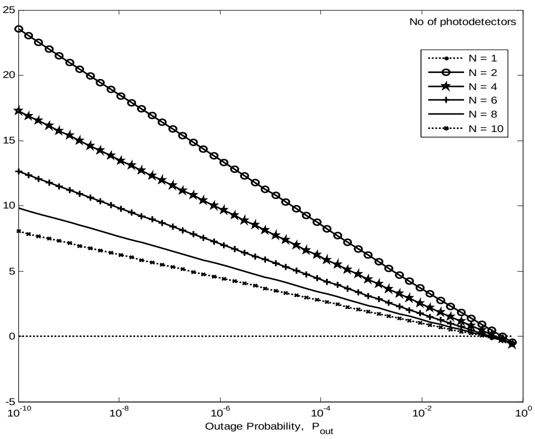

Fig. 5: Predicted SelC diversity gain (dB) per photodetector against P_{out} for $N = [1, 2, 4, 6, 10]$.

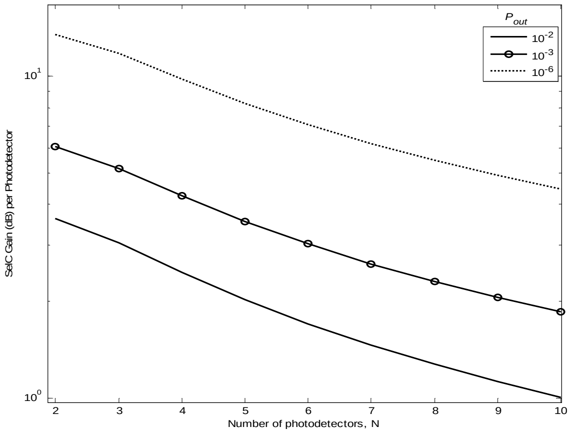

Fig. 6: Predicted SelC diversity gain (dB) per photodetector against N for $P_{out} = [10^{-6}, 10^{-3}, 10^{-2}]$.

It should be noted that up to 10 photodetectors has been considered in the results presented, this is mainly for illustration purpose. The use of such a large number of detectors will pose serious implementation difficulties. An interesting point to note from these results however, is that unlike in weak turbulence regime/short range links where previous studies [13] [27] revealed that SelC should not be used; SelC is highly recommended here as it results in a significant reduction in the required receiver sensitivity especially when the photodetector is kept to a maximum of four. An explanation for this is as follow. The irradiance fading in a fully developed speckle regime is dominant over the reduction in the received irradiance due to the reduction in the receiver aperture area. Any scheme that thus mitigates this dominant irradiance fading will clearly result in an improved performance.

The predicted sensitivities and diversity gains presented in this paper are valid for as long as the photodetectors receive independent irradiances. That is, $\rho_o < s \leq \vartheta_D L$ where ϑ_D is the divergence angle of the optical source in milliradian and L is the link length in kilometre. For $s < \rho_o$, the received irradiances are correlated, thus a reduced diversity gain.

V. CONCLUSIONS

The performance of a DPSK-SIM optical wireless communication link has been presented in fully developed speckle environment. Expressions for the BER and P_{out} performance metrics have been presented with and without the SelC spatial diversity. In the saturation regime under consideration, the fading is so strong that huge receiver sensitivity is usually required to achieve an acceptable level of performance. At say a BER of 10^{-6}, about 23 dBm of irradiance is required at the receiver while achieving a corresponding outage probability of 10^{-6} will require about 60 dBm sensitivity. These values are prohibitive and any technique such as the spatial diversity that mitigates the channel fading will hence result in huge gains. Results show that with two PIN photodetectors, a maximum gain of about 25 dB is predicted at a BER of 10^{-6}.

This implies therefore that the SelC spatial diversity is a potent technique for mitigating scintillation in the fully developed speckle regime as it results in a significant improvement in link performance especially when the photodetector is kept to a maximum of four.

APPENDIX A

Assumption 1: Let the number of independent photodetectors be N.

$$\therefore I_{max} = max\{I_i\}_{i=1}^{N}. \quad \text{(A1)}$$

And $p(I_{max}) = p(max\{I_i\}_{i=1}^{N})$. Considering an arbitrary received irradiance I, it then follows that

$p(I_{max} < I) = p(I_1 < I, I_2 < I, ...I_N < I)$ since none of the $\{I_i\}_{i=1}^{N}$ is greater than I_{max}.

The following therefore gives the cumulative distribution function (CDF) of I_{max} for N-independent received irradiances:

$$p(I_{max} < I) = \int_0^I ... \int_0^I \int_0^I p(I_1, I_2 ... I_N) dI_1 dI_2 ... dI_N. \quad \text{(A2)}$$

Assumption 2: The received irradiances are identically distributed as negative exponential distribution.

$$\begin{aligned} p(I_{max} < I) &= \prod_{i=1}^{N} \int_0^I p(I_i) dI_i = \left[\int_0^I \frac{1}{I_o} \exp\left(-\frac{I}{I_o} \right) dI \right]^N \\ &= \left(1 - \exp\left(-\frac{I}{I_o} \right) \right)^N \end{aligned} \quad \text{(A3)}$$

The required pdf $p(I_{max})$ is now obtained by differentiating (12) once with respect to the irradiance I.

$$\begin{aligned} p(I_{max}) &= \frac{d}{dI} \left(1 - \exp\left(-\frac{I}{I_o} \right) \right)^N \\ &= \frac{N}{I_o} \exp\left(-\frac{I}{I_o} \right) \left(1 - \exp\left(-\frac{I}{I_o} \right) \right)^{N-1}. \end{aligned} \quad \text{(A4)}$$

With $N = 1$, (A4) gives the negative exponential distribution as will be expected.

REFERENCES

[1] H. Willebrand and B. S. Ghuman, *Free Space Optics: Enabling optical Connectivity in today's network*. Indianapolis, SAMS publishing, 2002.

[2] Michele D'Amico, Angelo Leva, and B. Micheli, "Free-space optics communication systems: first results from a pilot field-trial in the surrounding area of Milan, Italy," *IEEE Microwave and Wireless Components Letters,* vol. 13, pp. 305-307, August 2003.

[3] C. J. Juan, D. Anurag, A. R. Hammons, D. J. Steven, Vijitha Weerackody, and A. N. Robert, "Free-Space Optical Communications for Next-generation Military Networks," *Communications Magazine, IEEE,* vol. 44, p. 46, 2006.

[4] E. Leitgeb, M. Geghart, and U. Birnbacher, "Optical networks, last mile access and applications," *Journal of Optical and Fibre Communications Reports,* vol. 2, pp. 56-85, 2005.

[5] J. D. Montgomery, "Free-space optics seen as viable alternative to cable," *Lightwave (Analyst corner),* pp. 43-44, 2004.

[6] S. Hardy, "Free-space optics systems are finding their niches," *Lightwave* pp. 33-36, Dec. 2005.

[7] C. H. Kwok, R. V. Penty, and I. H. White, "Link reliability improvement for optical wireless communication systems with temporal domain diveristy reception," *IEEE Photonics Technology Letters,* vol. 20, pp. 700-702, 2008.

[8] G. R. Osche, *Optical Detection Theory for Laser Applications*. New Jersey: Wiley, 2002.

[9] S. Karp, R. M. Gagliardi, S. E. Moran, and L. B. Stotts, *Optical Channels: fibers, cluds, water and the atmosphere*. New York: Plenum Press, 1988.

[10] M. A. Al-Habash, L. C. Andrews, and R. L. Phillips, "Mathematical model for the irradiance probability density function of a laser beam propagating through turbulent media," *Optical Engineering,* vol. 40, pp. 1554-1562, 2001.

[11] X. Zhu and J. M. Kahn, "Free-space optical communication through atmospheric turbulence channels," *IEEE Transactions on Communications,* vol. 50, pp. 1293-1300, August 2002.

[12] W. O. Popoola, Z. Ghassemlooy, J. I. H. Allen, E. Leitgeb, and S. Gao, "Free-space optical communication employing subcarrier modulation and spatial diversity in atmospheric turbulence channel," *IET Optoelectronic,* vol. 2, pp. 16-23, 2008.

[13] E. J. Lee and V. W. S. Chan, "Optical communications over the clear turbulent atmospheric channel using diversity," *IEEE Journal on Selected Areas in Communications,* vol. 22, pp. 1896-1906, 2004.

[14] X. Zhu and J. M. Kahn, "Performance bounds for coded free-space optical communications through atmospheric turbulence channels," *IEEE Transaction on Communications,* vol. 51, pp. 1233-1239, August 2003.

[15] H. Yamamoto and T. Ohtsuki, "Atmospheric optical subcarrier modulation systems using space-time block code," in *IEEE Global Telecommunications Conference, (GLOBECOM '03)* vol. 6, New York, pp.3326-3330, 2003.

[16] I. B. Djordjevic, B. Vasic, and M. A. Neifeld, "LDPC coded OFDM over the atmospheric turbulence channel," *Optical Express,* vol. 15, pp. 6336-6350, 2007.

[17] J. Li, J. Q. Liu, and D. P. Taylor, "Optical communication using subcarrier PSK intensity modulation through atmospheric turbulence channels," *IEEE Transaction on Communications,* vol. 55, pp. 1598-1606, 2007.

[18] S. Sheikh Muhammad, T. Javornik, I. Jelovcan, Z. Ghassemlooy, and E. Leitgeb, "Comparison of hard-decision and soft-decision channel coded M-ary PPM performance over free space optical links," *European Transaction on Telecommunications,* pp. 12, DOI: 10.1002/ett.1343, 2008.

[19] J. G. Proakis, *Digital Communications*. New York: McGraw-Hill, 2004.

[20] K. Kiasaleh, "Performance of coherent DPSK free-space optical communcation systems in K- distributed turbulence," *IEEE Transaction on Communications,* vol. 54, pp. 604-607, 2006.

[21] R. M. Gagliardi and S. Karp, *Optical Communications*, 2nd Edition ed. New York: John Wiley, 1995.

[22] N. S. Kopeika and J. Bordogna, "Background noise in optical communication systems," *Proceedings of the IEEE,* vol. 58, pp. 1571-1577, 1970.

[23] W. K. Pratt, *Laser Communication Systems*, 1st ed. New York: John Wiley & Sons, Inc., 1969.

[24] S. Karp, E. L. O'Neill, and R. M. Gagliardi, "Communication theory for the free-space optical channel," *Proceedings of the IEEE,* vol. 58, p. 1611, 1970.
[25] J. H. Churnside and S. F. Clifford, "Log-normal Rician probability density function of optical scintillations in the turbulent atmosphere," *Journal of Optical Society of America,* vol. 4, pp. 1923-1930, 1987.
[26] L. C. Andrews and R. L. Phillips, "I-K distribution as a universal propagation model of laser beams in atmospheric turbulence," *Journal of optical society of America A,* vol. 2, p. 160, Feb. 1985 1985.
[27] W. O. Popoola, Z. Ghassemlooy, and E. Leitgeb, "Free-space optical communication in atmospheric turbulence using DPSK subcarrier modulation," in *Ninth International Symposium on Communication Theory and Applications ISCTA'07*, Ambleside, Lake District, UK, 2007.
[28] I. S. Gradshteyn and I. M. Ryzhik, *Table of integrals, series, and products*, 5th ed. London: Academic Press, Inc., 1994.
[29] V. W. S. Chan, "Free-space optical communications," *IEEE Journal of Lightwave Technology,* vol. 24, pp. 4750-4762, 2006.

Wasiu O. Popoola received the ND in electrical engineering from The Federal Polytechnic, Ilaro, Nigeria, and later received the B.Sc. degree (first class Hons) in electronic and electrical engineering from Obafemi Awolowo University, Ile-Ife, Nigeria. He received the M.Sc. degree (with distinction) in optoelectronic and communication systems from Northumbria University, Newcastle upon Tyne, U.K., in 2006, where he is currently working toward the Ph.D. degree.

He worked briefly as a Teaching Assistant at Nnamdi Azikiwe University, Nigeria, between 2003 and 2004. His research interests include optical communication (fiber and wireless), digital communication and digital signal processing. He also works as Research/Teaching Assistant in the Northumbria Communication Research Laboratory. His research is partly sponsored by the British government under the ORSAS award and he also holds Northumbria University research studentship.

Mr. Popoola is student member of IEEE, IET and an associate member of the Institute of Physics (IoP).

Professor Zabih Ghassemlooy CEng, Fellow of IET, Senior Member of IEEE: Received his BSc (Hons) degree in Electrical and Electronics Engineering from the Manchester Metropolitan University in 1981, and his MSc and PhD in Optical Communications from the University of Manchester Institute of Science and Technology (UMIST), in 1984 and 1987, respectively with Scholarships from the Engineering and Physical Science Research Council, UK. From 1986-87 he worked as a Demonstrator at UMIST and from 1987 to 1988 he was a Post-doctoral Research Fellow at the City University, London. In 1988 he joined Sheffield Hallam University as a Lecturer, becoming a Reader in 1995 and a Professor in Optical Communications in 1997. He was the Group Leader for Communication Engineering and Digital Signal Processing, and also head of Optical Communications Research Group until 2004. In 2004 he moved to the University of Northumbria at Newcastle as an Associate Dean for Research in the School of Computing, Engineering and Information Sciences.

He also heads the Northumbria Communications Research Laboratories within the School. He was the coordinator for the successful RAE 2008 submission in the General Engineering with more than 50% of the work submitted rated as 4* and 3*. In 2001 he was a recipient of the Tan Chin Tuan Fellowship in Engineering from the Nanyang Technological University in Singapore to work on the photonic technology. In 2006, he was awarded one of the best PhD research supervisors at Northumbria University. He was a visiting professor at the Ankara University, Turkey and Hong-Kong Polytechnic University, and is currently a visiting Professor at the Technological University of Malaysia.

He is the Editor-in-Chief of The Mediterranean Journals of Computers and Networks, and Electronics and Communications. He currently serves on the Editorial Committees of IEEE Communications Letters, International Journal of Communication Systems, Journal of Electrical and Computer Engineering, Iranian Journal Electrical and Electronic Engineering, the EURASIP Journal of Wireless Communications and Networking, Contemporary Engineering Sciences, Research Letter in Signal Processing, and also has served on the Publication Committee of the IEEE Transactions on Consumer Electronics, the editorial board of the Inter and the Sensor Letters. He is the founder and the Chairman of the International Symposium on Communication Systems, Network and Digital Signal Processing, a committee member of The International Institute of Informatics and Systemics, and is a member of technical committee of a number of international conferences. He is a College Member of the Engineering, and Physical Science Research Council, UK (2003-2009), and has served on a number international Research and Advisory Committees.

His research interests are in the areas of photonic networks, modulation techniques, high-speed optical systems, optical wireless communications as well as optical fibre sensors. He has received a number of research grants from UK Research Councils, European Union, Industry and UK Government. He has supervised a large number of PhD students and has published over 320 papers (120 in journals). He is a co-editor of an IET book on “Analogue Optical Fibre Communications”, the proceedings of the CSNDSP ‘08’, ’06, CSDSP’98, and the 1st Intern. Workshop on Materials for Optoelectronics 1995, UK. He is the co-guest editor of a number of special issues: the IET Proceeding Circuit, Devices and Systems, August 2006, Vol. 2, No. 1, 2008, the Mediterranean J. of Electronics and Communications on “Free Space Optics –RF”, July 2006, the IET Proceeding J. 1994, and 2000, and Inter. J. Communications Systems 2000. From 2004-06 he was the IEEE UK/IR Communications Chapter Secretary and the Vice-Chairman and currently is the Chairman.

Erich Leitgeb was born in 1964 in Fürstenfeld (Styria, Austria) and received his master degree (Dipl.-Ing. in electrical engineering) at the Technical University of Graz in 1994. From 1982 to 1984 he attended a training to become an officer for Communications in the Austrian army, (his current military rank is Major). In 1994 he started research work in Optical Communications and RF at the

Department of Communications and Wave Propagation (TU Graz). In February 1999 he received his PhD-degree (Dr. at the University of Technology Graz) with honours. He is currently Associate Professor at the University of Technology Graz.
Since January 2000 he is project leader of international research projects in the field of optical communications and wireless communications (like COST 270 the EU project SatNEx (a NoE), COST 291 and currently COST IC0802 and SatNEx II). He is giving lectures in Optical Communications Engineering, Antennas and Wave Propagation and Microwaves. In 2002 he had a research stay at the department of Telecommunications at Zagreb University, Croatia and in 2008 at the University of Ljubljana, Slovenia. He is a Member of IEEE, SPIE and WCA. Since 2003 he is reviewer for IEEE and SPIE conferences and journals and he acts as member of Technical Committees and Chairpersons on these conferences. He was guest editor of a special issue (published 2006) in the Mediterranean Journal of Electronics and Communications on "Free Space Optics – RF" and also of a special issue (published 2007) in the European Microwave Association Journal of on "RFID technology". Since 2007 he prepared the international IEEE conference CSNDSP 08 (July 2008) in Graz as local organizer. In May 2009 he was a Guest Editor on the Special Issue on Radio Frequency Identification (RFID) in the IEEE Transactions on Microwave Theory and Techniques. In July 2009 he acts as a Guest Editor on the Special Issue on RF-Communications in the Mediterranean Journal of Electronics and Communications (selected papers from the CSNDSP 08).