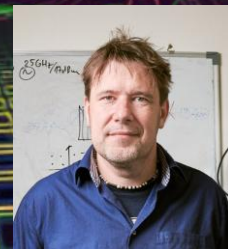


Free Space Optical Communications – Part III – Turbulence and Pointing Errors

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FSO - Challenges

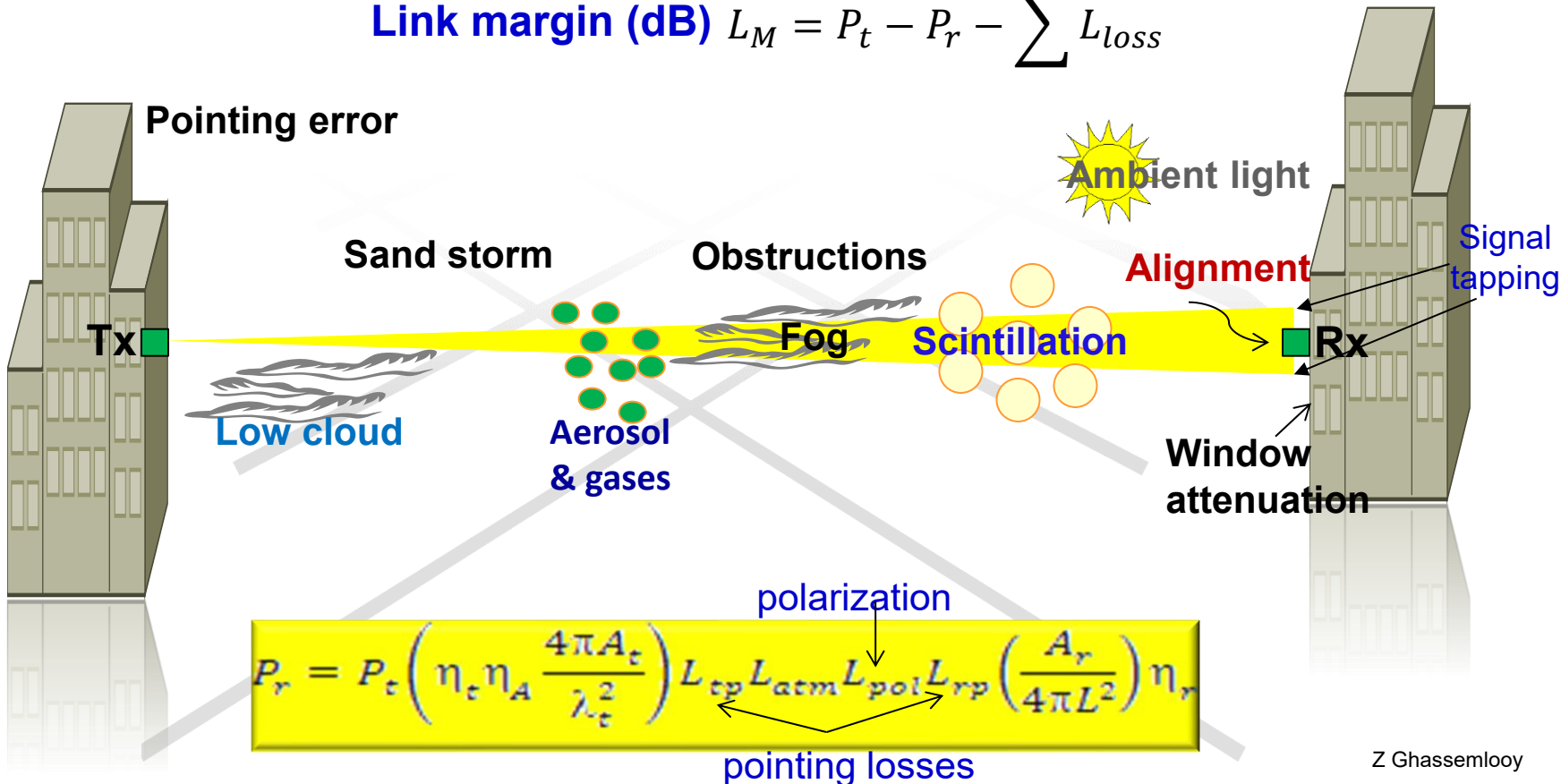
- Terrestrial
 - Atmospheric conditions
 - Turbulence
 - Pointing errors
 - Additional challenges - Jamming
 - Final comments

FSO - Challenges

Channel behaves like a time varying attenuator:

- Channel loss (randomly time varying) due to pointing errors and scintillation
- Attenuation: Fixed geometric spreading + Atmospheric attenuation
- Noise

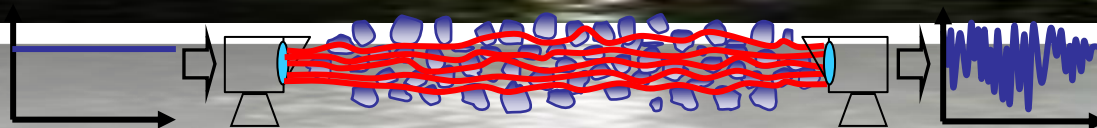
Link margin (dB) $L_M = P_t - P_r - \sum L_{loss}$



FSO Turbulence

FSO – Turbulence Challenges

Cause: Atmospheric inhomogeneity / random temperature variation along beam path.
→ changes in refractive index of the channel

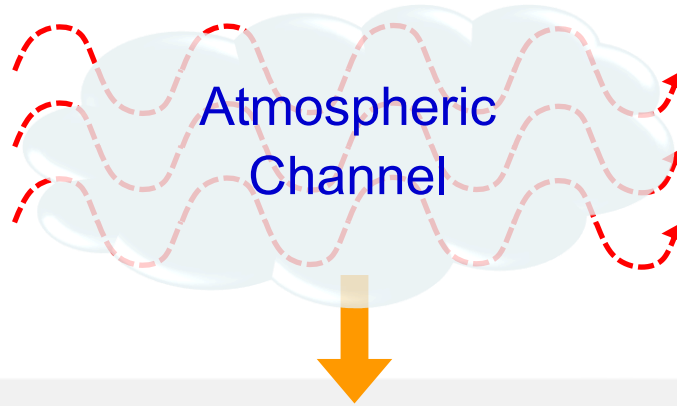


| Effects | Options | Remarks |
|--|--|--|
| <ul style="list-style-type: none"> ■ Irradiance fluctuation (scintillation) ■ Image dancing ■ Phase fluctuation ■ Beam spreading ■ Polarisation fluctuation | <ul style="list-style-type: none"> ■ Diversity techniques ■ Forward error control ■ Robust modulation techniques ■ Adaptive optics ■ Coherent detection can't be used without turbulence compensation | <ul style="list-style-type: none"> ■ Significant for long link range (>1km) ■ Turbulence and thick fog do not occur together ■ In IM/DD, it results in deep irradiance fades that could last up to ~1-100 μs |

FSO Challenges - Turbulence



Transmitter



Receiver

Highly **variable**, **unpredictable** and **vulnerable**

- **Weather** dependence
- Aerosol **scattering** and **absorption**
- Atmospheric **turbulence**

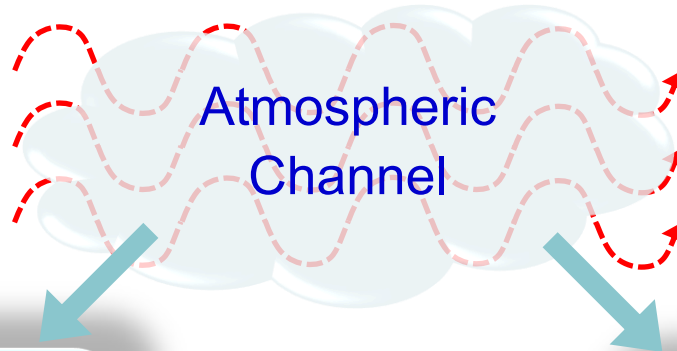
Presence of **pointing errors**

X. M. Zhu and J. M. Kahn, "Free-space optical communication through atmospheric turbulence channels," IEEE Transactions on Communications, vol. 50, no. 8, pp. 1293–1330, Aug. 2002.

FSO Challenges - Turbulence



Transmitter



Receiver

Turbulence

Scintillation - a specific instance of turbulence

Refractive index fluctuations

Thermal gradients → turbulent eddies

} Interference
in the wave
front
aberrations

Beam wandering

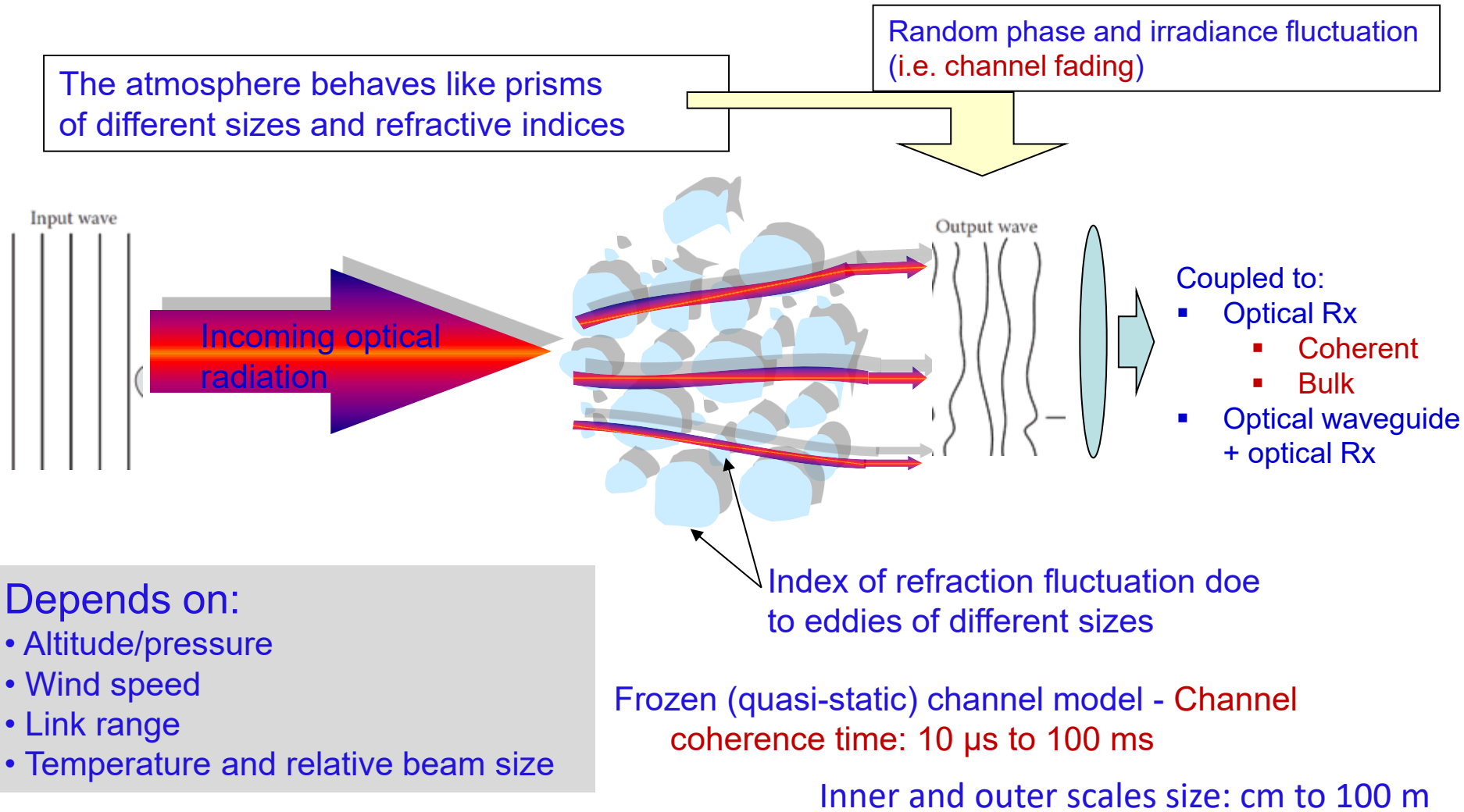
Interaction between the laser beams and randomly floating turbulent eddies

Aerosols and
molecules

→ Optical power
attenuation

→ Reduced link range

FSO Challenges - Turbulence



FSO – Simulation of The Optical Beam Propagation

Numerical Analysis [1]

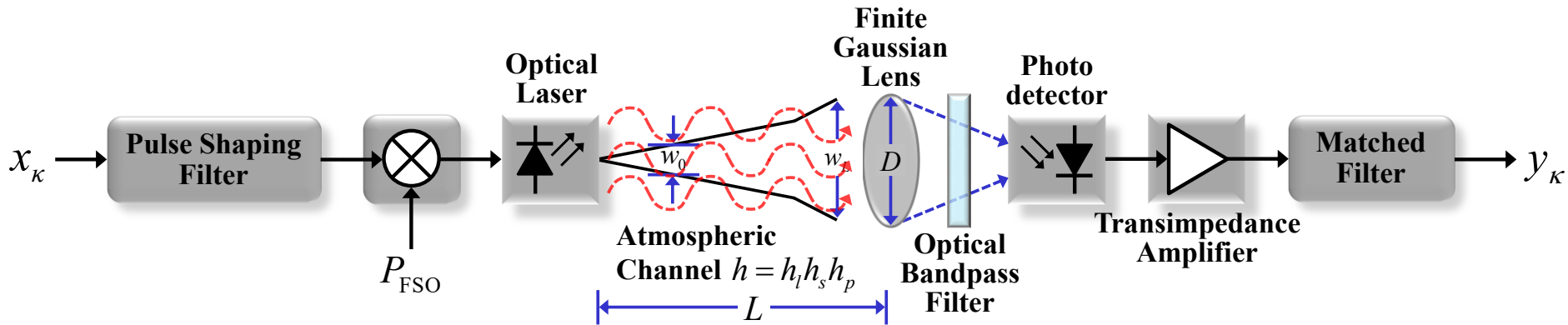
- Based on Fast Fourier transform.
- Capturing the optical beam wavefront using the phase screens technique, providing a more detailed description of the optical signal propagation through the free space.
- But is computationally intensive.

Statistical Analysis [1]

- Intensity-based for direct detection
- Phase-based for coherent detection
- Is used for attenuation due to the beam diffraction, atmospheric scintillation, pointing errors, the Doppler effect, and scintillation-induced divergence.

See an excellent OPTICA webinar on “Simulation and Design Framework for FSO: https://www.optica.org/events/webinar/2025/12_december/simulation_and_design_framework_for_free-space_optical_communication/”

FSO – Turbulence- System Model



Single-input single-output
(**SISO**)

Horizontal FSO
communication link



- Turbulent channel
- Beam extinction
- Pointing error

Intensity modulation
with direct detection
(**IM/DD**)

Non-return-to-zero
on-off-keying
(**NRZ-OOK**)

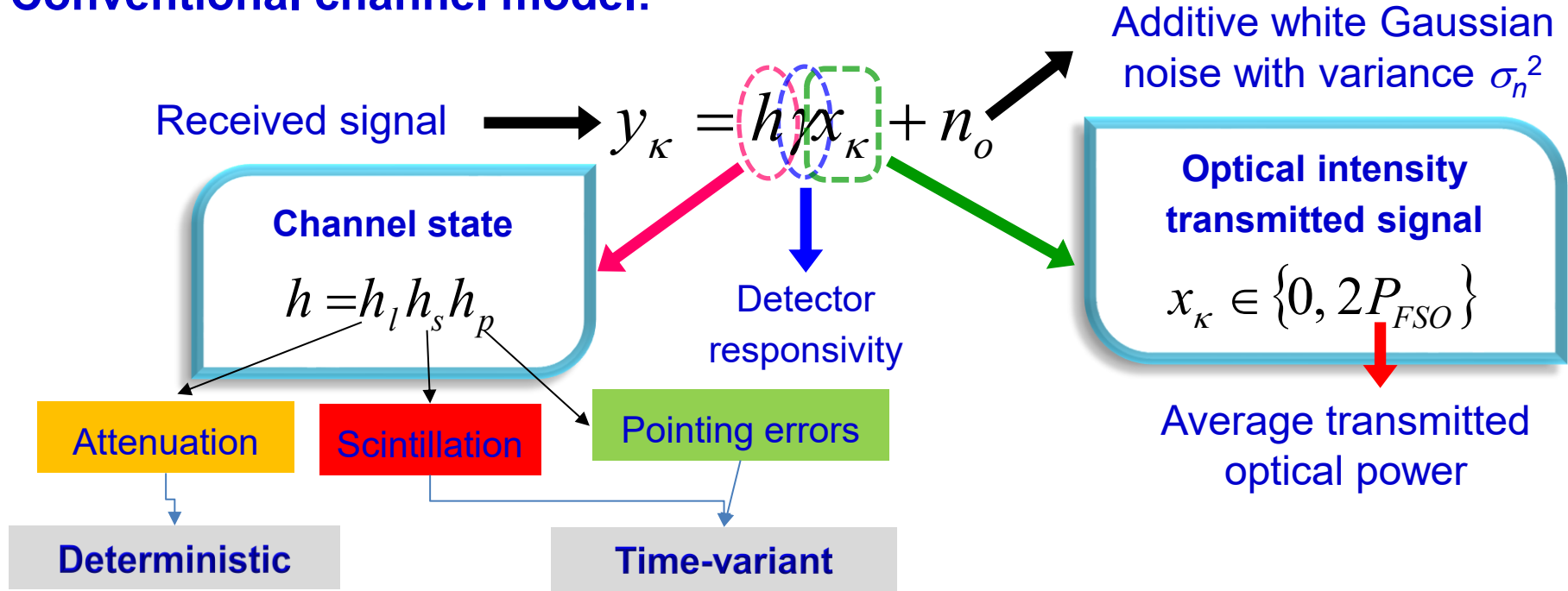
Gaussian-beam wave -

Using the fundamental lowest-order transverse electromagnetic mode (**TEM₀₀**) mode, used as a baseline outputs in many laser

Finite **Gaussian lens** for **converging the beam**

FSO – Turbulence- System Model

Conventional channel model:



- A **fluctuating** term due to the **influence of h**
- Chosen from the **random ensemble** according to the **distribution $f_h(h)$**

Received electrical SNR

$$SNR(h) = \frac{2P_{FSO}^2 \gamma^2 h^2}{\sigma_n^2}$$

FSO – Gaussian Beam Model

TEM₀₀ Gaussian-beam wave

- Gaussian amplitude distribution
- Effective beam radius w_0 at the Tx
- The **receiving beam size**:

$$w_L = w_0 \sqrt{\Theta_n^2 + \zeta \Lambda_n^2}$$

Normalized components:

$$\Theta_n = \frac{F_0 - L}{F_0}$$

$$\Lambda_n = \frac{\lambda L}{\pi w_0^2}$$

Phase front radius of curvature at the transmitter

Global coherence parameter:

$$\zeta = \zeta_s + \frac{2w_0^2}{\rho_0^2}$$

Coherence of the beam

Coherence length of the spherical wave:

$$\rho_0 = \left[0.55 C_n^2 (2\pi/\lambda)^2 L \right]^{3/5}$$

Turbulence strength

FSO – Gaussian Beam Model

Point-receiver scintillation index:

$$\sigma_I^2(0) \cong 4.42 \sigma_R^2 \Lambda_L^{5/6} \frac{\rho^2}{w_L^2} + 3.86 \sigma_R^2 \left\{ 0.40 [(1 + 2\Theta_L)^2 + 4\Lambda_L^2]^{5/12} \right. \\ \left. \times \cos \left[\frac{5}{6} \tan^{-1} \left(\frac{1 + 2\Theta_L}{2\Lambda_L} \right) \right] - \frac{11}{16} \Lambda_L^{5/6} \right\}$$

Due to **beam wander** effects

Receiver beam parameters:

$$\Theta_L = \frac{F_L + L}{F_L} \quad \Lambda_L = \frac{\lambda L}{\pi w_L^2}$$

Phase front radius of curvature at the receiver

$$F_L = \frac{L(\Theta_n^2 + \zeta \Lambda_n^2)}{\phi \Lambda_n - \zeta \Lambda_n^2 - \Theta_n^2}$$

$$\phi \equiv \frac{\Theta_n}{\Lambda_n} - \frac{\Lambda_n w_0^2}{\rho_0^2}$$

Rytov variance:

$$\sigma_R^2 = 1.23 C_n^2 \left(\frac{2\pi}{\lambda} \right)^{7/6} L^{11/6}$$

FSO – Aperture Averaging

- Aperture size increases beyond the irradiance correlation width
- Receiver “sees” several **correlation patches**
- **Scintillation** level measured by the detector in the image plane begins to decrease
- **Aperture averaging** factor:

$$A_G = \frac{\sigma_I^2(D)}{\sigma_I^2(0)} = \frac{16}{\pi} \int_0^1 x dx \exp \left\{ -\frac{D^2 x^2}{\rho_0^2} \left(2 + \frac{\rho_0^2}{w_0^2 \Lambda_n^2} - \frac{\rho_0^2 \phi^2}{w_L^2} \right) \right\}$$

$$\times \left[\cos^{-1}(x) - x \sqrt{1 - x^2} \right]$$

Aperture-averaged scintillation index

Receiver aperture diameter

$$x = \frac{\rho}{D}$$

FSO Challenges - Turbulence

- Air temperature and density variations → thermal gradients → randomly distributed cells with different reflective index.

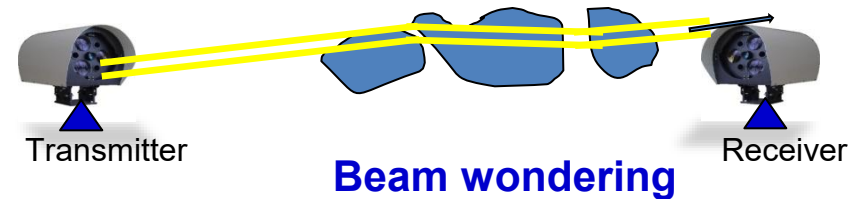
$$n(R,t) = n_o + n_1(R,t)$$

n_o is mean index of refraction ($n_o = 1$), $n_1(R,t)$ is the random deviation of index from its mean value, R is the vector position in three dimension and t is the time.

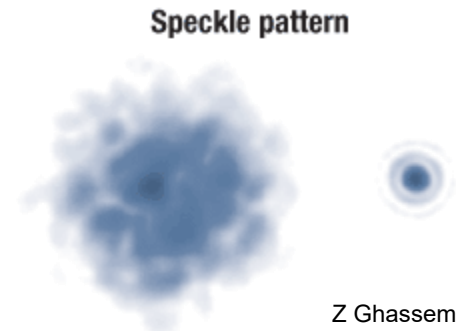
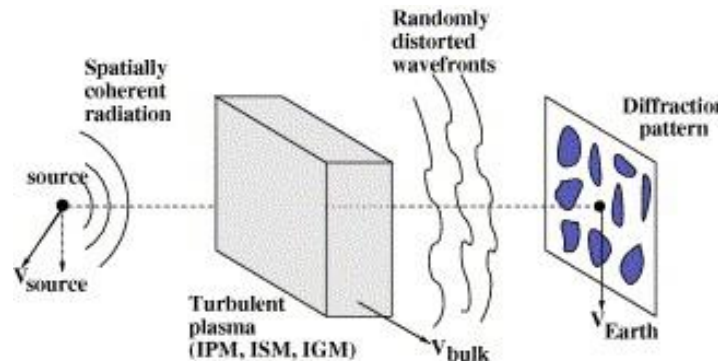
$$n = 1 + 77.6(1 + 7.52 \times 10^{-3} \lambda^{-2}) \frac{P}{T_e} \times 10^{-6}$$

$$-dn/dT_e = 7.8 \times 10^{-5} P/T_e^2$$

P : Channel pressure, T_e : Channel temperature



- In imaging detector it causes speckle pattern



FSO Turbulence – Characterisation

- To characterise the atmospheric turbulence based on the altitude h (m) of the atmosphere, the widely used **index of refraction structure parameter (turbulence strength)**

$$C_n^2(h) = 0.005(v_w/27)^2(10^{-5}h)^{10} \exp(-h/1000) + 2.7 \times 10^{-6} \exp(-h/1500) + \hat{A} \exp(-h/100),$$

$$C_n^2 = \left(86 \cdot 10^{-6} \frac{P}{T^2} \right)^2 \cdot \frac{(T_1 - T_2)^2}{R^2}$$

where \hat{A} is a normal value of $C_n^2(0)$ at the ground level in $m^{-2/3}$, and $v_w \sim 21$ m/s. The value of C_n^2 varies with h of the atmosphere, however, it is almost considered to be constant for a horizontally propagating field.

The typical average values of C_n^2 is $10^{-12} m^{-2/3}$ and $10^{-17} m^{-2/3}$ for the strong and weak turbulence regimes, respectively

FSO - Turbulence Characterisation

Indirectly from temperature variance (temperature gradient)

- 1- The temperature difference is obtained from point measurements of the mean-square temperature difference between two thermometers.
- 2- This allows to **determine** C_T^2 (temperature structure constant) or any given length L using:

$$D_{T_e}(L) = \langle (T_a - T_b)^2 \rangle = \begin{cases} C_T^2 l_o^{-4/3} L^2, & 0 \leq L \ll l_o \\ C_T^2 L^{2/3}, & l_o \ll L \ll L_o \end{cases}$$

l_o and L_o represent the small and large sizes of eddies, respectively.

- 3- The values of the refractive index fluctuation can be obtained from.

$$\frac{dn_1}{dT} = -\frac{77.6P}{T_e^2} \times 10^{-6}.$$

- 4- Thus, the values of the C_n^2 can be inferred directly by using:

$$C_n^2 = \left(\frac{dn_1}{dT} \right)^2 C_T^2.$$

FSO Turbulence – Characterisation

Scintillation index: is a viable statistical quantitative measure of the magnitude of atmospheric turbulence-induced irradiance fluctuations I (i.e., the level of scintillations)

$$\sigma_I^2 = E\{I^2\} / E\{I\}^2 - 1$$

- Rytov variance:**

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$$

Wave number $k = 2\pi/\lambda$
 L – Link span

Used for classification of atmospheric turbulence-induced scintillations

Weak turbulence regime: $C_n^2 = 7 \times 10^{-16} \text{ m}^{-2/3}$, $L = 500\text{m}$, $\sigma_R^2 = 0.004$
 $\sigma_R^2 \ll 1$; $\sigma_I^2 \approx \sigma_R^2$

Moderate turbulence regime: $C_n^2 = 4.58 \times 10^{-13} \text{ m}^{-2/3}$, $L = 500\text{m}$, $\sigma_R^2 = 2.56$
 $\sigma_R^2 \sim 1$

Strong turbulence regime: $C_n^2 = 4.58 \times 10^{-13} \text{ m}^{-2/3}$, $L = 1500\text{m}$, $\sigma_R^2 = 19.18$
 $\sigma_R^2 \gg 1$

FSO Turbulence – Statistical modelling

- To evaluate and characterise the turbulence based on theory is very challenging and complex.
 - The observable atmospheric channel quantities (temperature, pressure, aerosols and wind velocity) are mixed and behave in a non-linear fashion.
 - Therefore, the atmospheric turbulence can be simply expressed and characterised based on the **statistical distributions** e.g., probability distribution function of received irradiance and its related properties.

- **Proposed models**
 - Log-Normal - **Weak turbulence regime**; simple; tractable
 - Negative exponential – **Saturation regime only**
 - Rayleigh, K - **Strong turbulence regime**
 - Doubly-stochastic models - **Any turbulence regime**
 - I-K, α - μ , log-normal exponential, exponentiated Weibull, log-normal Rice, Generalized-K or Gamma-Gamma ($\Gamma\Gamma$).

FSO Turbulence – Statistical modelling

➤ Most reported models for irradiance fluctuation in turbulent channels:

✓ Log-normal (weak regimes)

$$p(I) = \frac{1}{\sqrt{2\pi\sigma_I^2}} \frac{1}{I} \exp\left\{-\frac{(\ln(I/I_0) - E[I])^2}{2\sigma_I^2}\right\} \quad I \geq 0$$

✓ Gamma–gamma (weak-to-strong regimes)

$$p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta/2)-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \quad I > 0$$

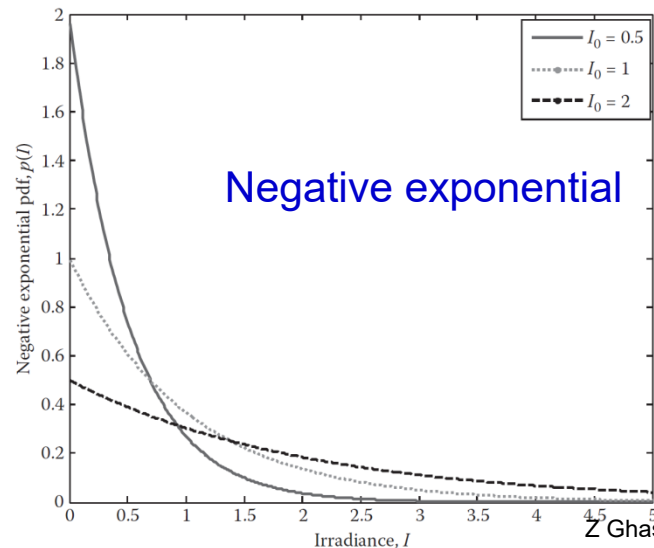
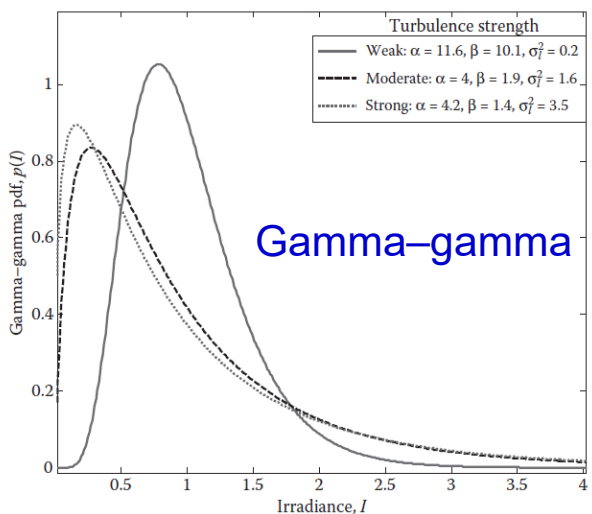
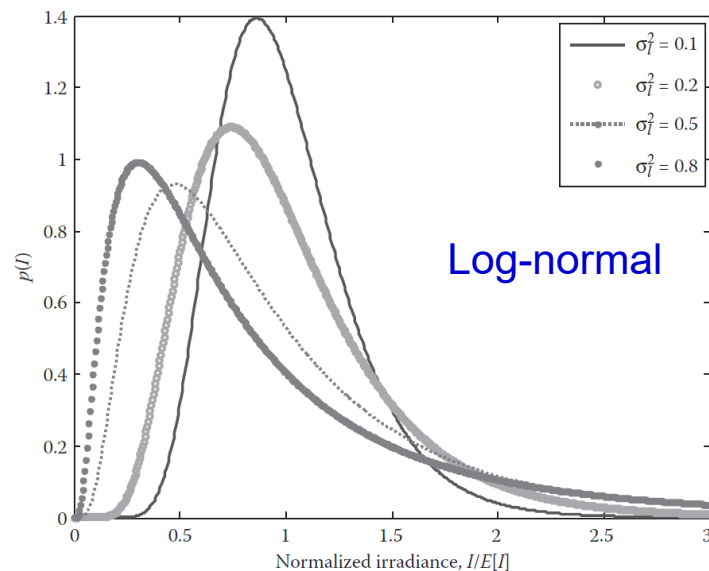
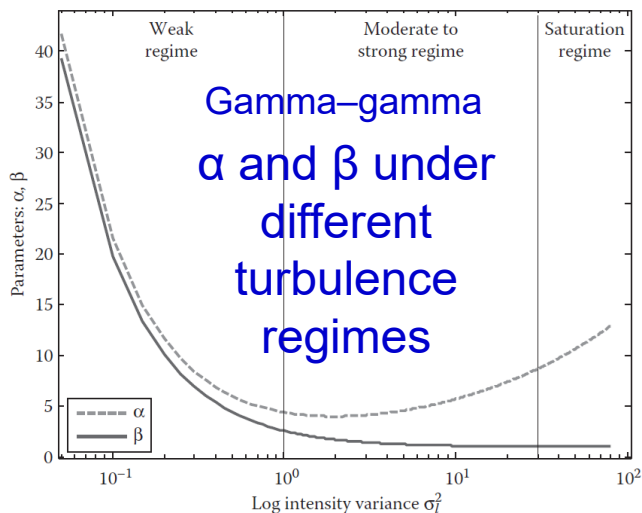
✓ K-distribution (very strong regimes)

$$f_{h_a}(h_a) = \frac{2\alpha^{\frac{\alpha+1}{2}}}{\Gamma(\alpha)} h_a^{\frac{\alpha-1}{2}} K_{\alpha-1}\left(2\sqrt{\alpha h_a}\right), \quad h_a > 0$$

✓ Negative exponential (saturated regimes)

$$p(I) = \frac{1}{I_0} \exp\left(-\frac{I}{I_0}\right) \quad I_0 > 0$$

FSO Turbulence – Statistical modelling



FSO Turbulence – Statistical modelling

Log Normal Simple; tractable but for weak regime only

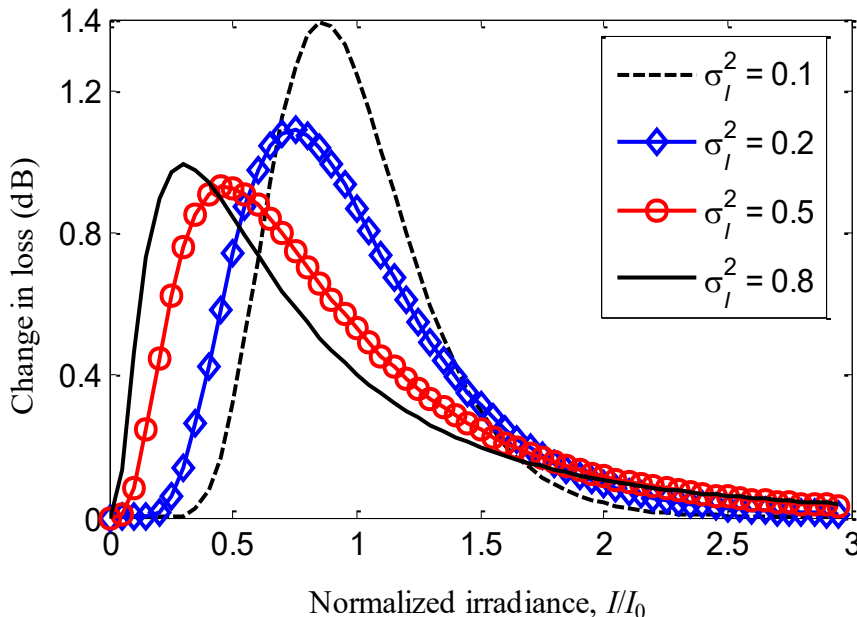
Irradiance PDF :

$$p_I(I) = \frac{1}{\sqrt{2\pi}\sigma_I} \frac{1}{I} \exp\left\{-\frac{(\ln(I/I_0) + \sigma_I^2/2)^2}{2\sigma_I^2}\right\} \quad I \geq 0$$

- I : Received irradiance
- I_0 : mean irradiance without turbulence
- σ_I^2 : Log irradiance variance (turbulence strength indicator)

$$\sigma_I^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$$

| Turbulence | SI |
|------------|-------|
| Weak | < 0.3 |
| Medium | ≈ 1 |
| Strong | >> 1 |



Note that, as the value of σ increases, the distribution becomes more skewed with longer tails towards the infinity.

This explains the extent of intensity fluctuations as the channel heterogeneity increases due to atmospheric turbulence.

FSO Turbulence – Statistical modelling

Gamma-Gamma

All regimes

Small-scale irradiance fluctuations modulated by large-scale fluctuations

Irradiance PDF by Andrews et al (2001):

$$p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\frac{\alpha+\beta}{2}-1)} K_{\alpha-\beta}(2\sqrt{\alpha\beta I})$$

$$\alpha = \left[\exp\left(\frac{0.49\sigma_I^2}{(1 + 1.11\sigma_I^{12/5})^{7/6}} \right) - 1 \right]^{-1}$$

$$\beta = \left[\exp\left(\frac{0.51\sigma_I^2}{(1 + 0.69\sigma_I^{12/5})^{5/6}} \right) - 1 \right]^{-1}$$

I_x : due to large scale effects;
obeys Gamma distribution

I_y : due to small scale effects;
obeys Gamma distribution

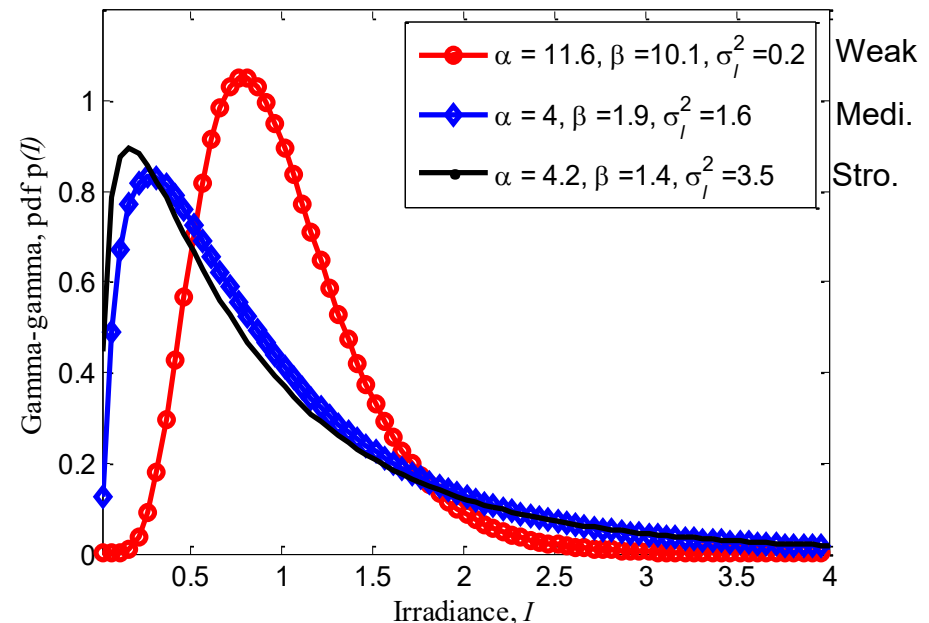
$K_n(\cdot)$: modified Bessel function
of the 2nd kind of order n

σ_I^2 : Log irradiance variance
(turbulence strength indicator)

the normalised received irradiance I is defined as the product of two statistically independent random processes I_x and I_y :

$$I = I_x I_y$$

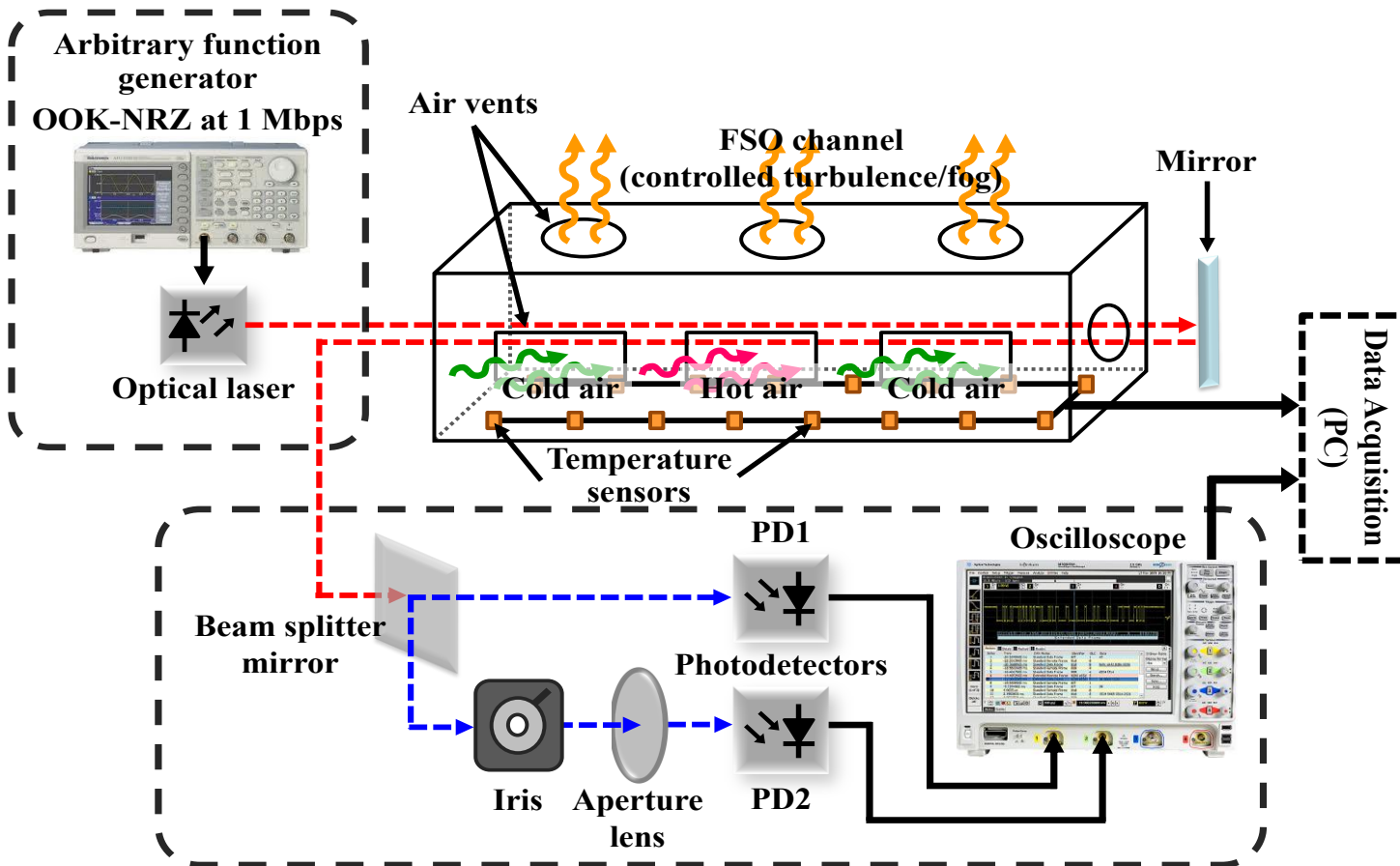
$I > 0$



as the turbulence increases the distribution spreads out more.

FSO Turbulence – Measurement

FSO Turbulence – Measurement



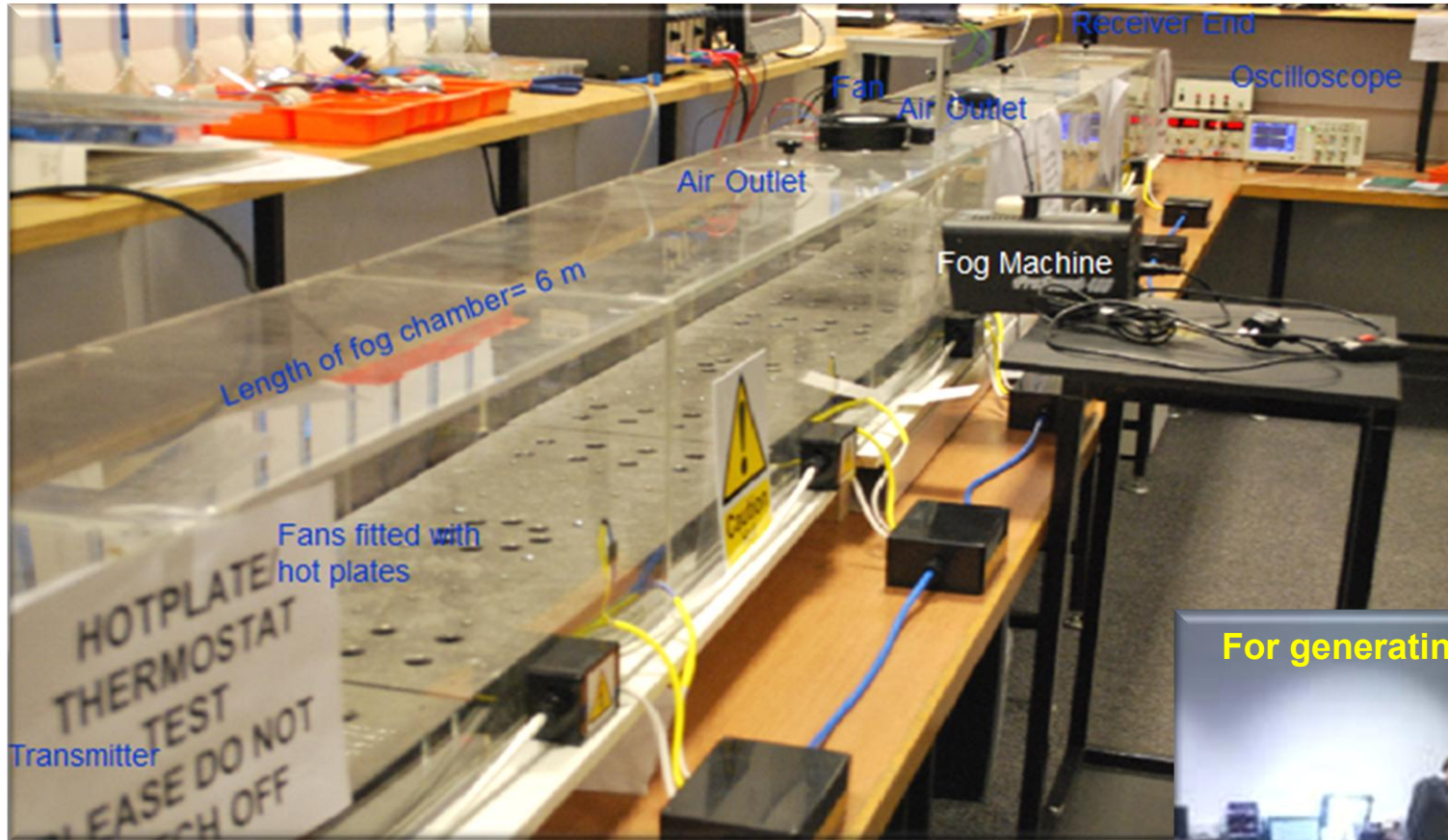
Two approaches of predicting scintillation index:

- Temperature gradient
- Optical signal statistics

$$\sigma_x^2 = 0.56k^{7/6} \int_0^{L_p} C_n^2(x)(L_p - x)^{5/6} dx$$

$$C_n^2 = \left(86 \times 10^{-6} \frac{P}{T^2} \right)^2 C_T^2$$

FSO Turbulence – Atmospheric Chamber

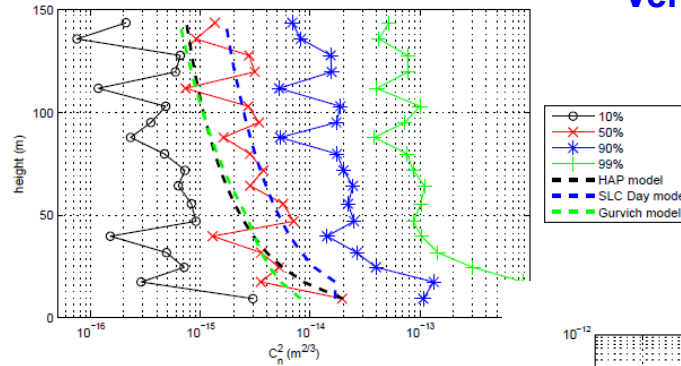
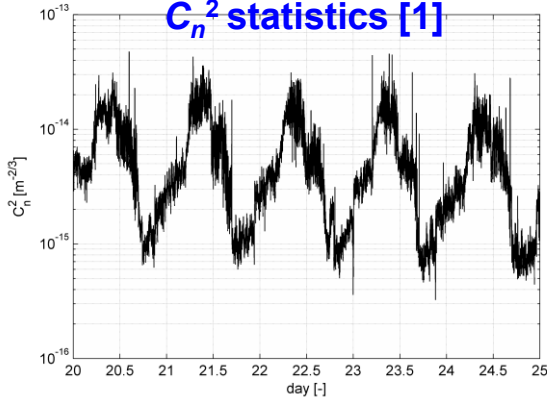


Atmospheric chambers, OCRG

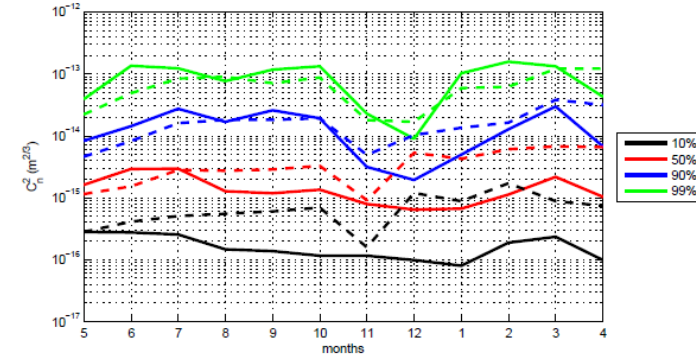


FSO - Turbulence Measurement

Horizontal measurements of C_n^2 statistics [1]

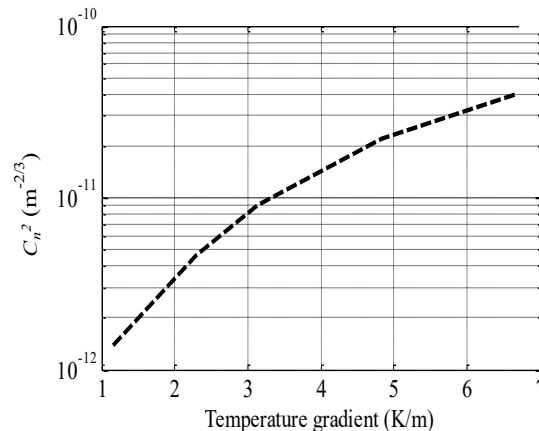


Vertical measurements C_n^2 statistics [2]



Using $C_n^2 = \left(\frac{dn_1}{dT} \right) C_T^2$.

To predict S.I. in the indoor chamber, it is assumed that C_n^2 is constant between two measured temperature points.



[1] J. Libich, S. Zvánovec.: Influences of Turbulences in Near Vicinity of Buildings on Free-space Optical Links. IET Microwaves, Antennas & Propagation. 2011, vol. 9, no. 5, p. 1039-1044. ISSN 1751-8725.

[2] O. Jicha, P. Pechac, S. Zvanovec, M. Grabner, V. Kvicera, "Long-term Measurements of Refractive Index Structure Constant in Atmospheric Boundary Layer," SPIE, 2012.

FSO - Turbulence Measurement

Measured values are obtained from the received signal using:

$$\sigma_l^2 = \frac{\sigma_l^2}{I_0^2} - 1,$$

Initial irradiance

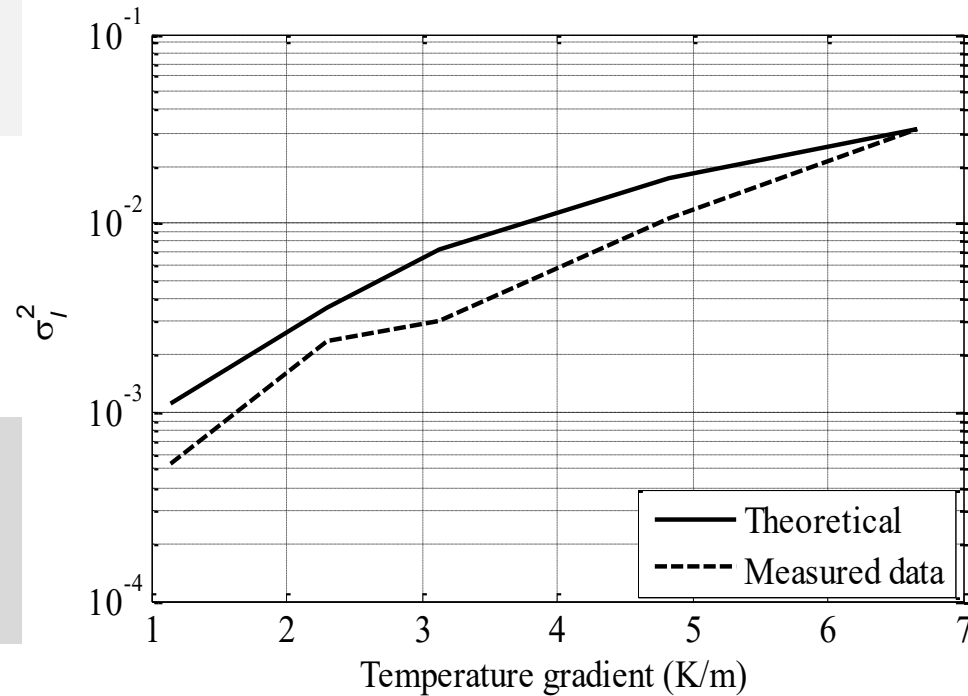
PD detection area (1 mm²) is comparable to the transverse coherence distance (~ 2.8 mm) calculated. Thus, aperture averaging factor A should be used for a plane wave propagation.

$$A = \frac{\sigma_l^2(D)}{\sigma_l^2(0)},$$

aperture-averaged scintillation index

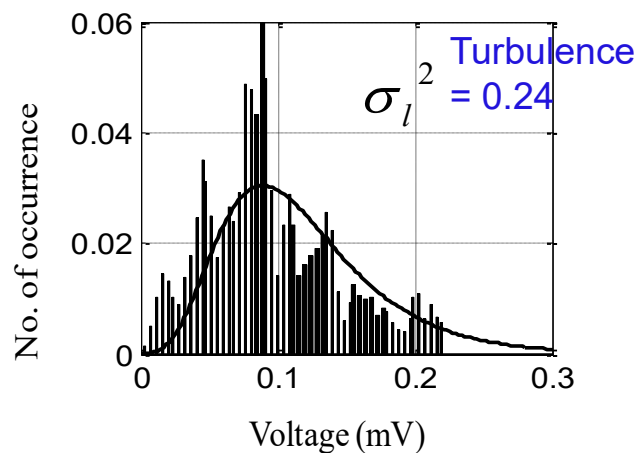
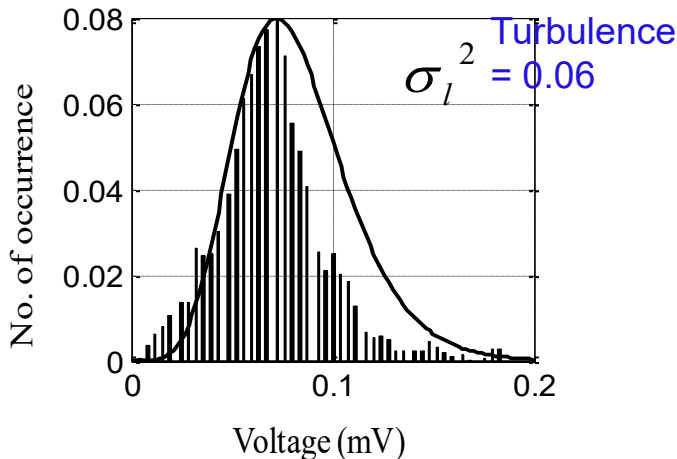
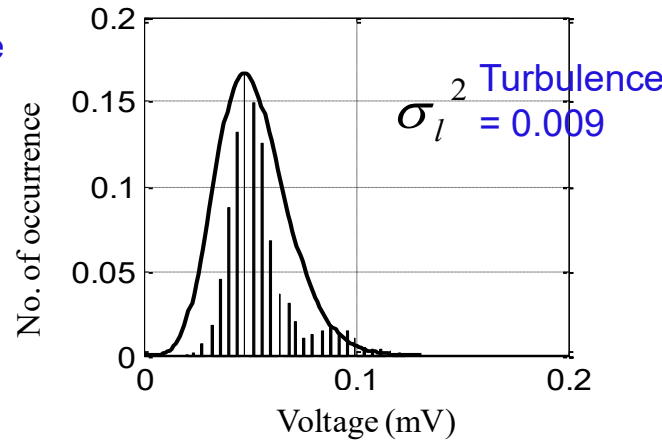
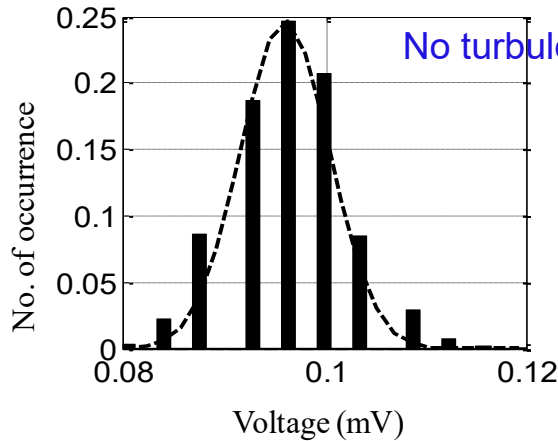
$\sigma_l^2(0)$ $\sigma_l^2(D)$ denotes the scintillation index for a receiver lens of diameter D and a "point receiver" ($D \approx 0$), respectively.

Therefore $\sigma_l^2 = 0.88 \sigma_D^2$, where $A = 0.88$



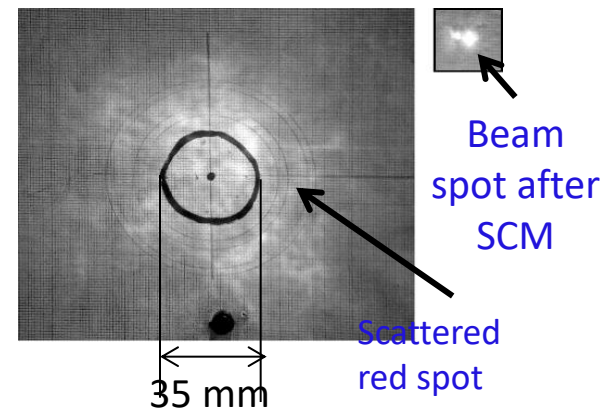
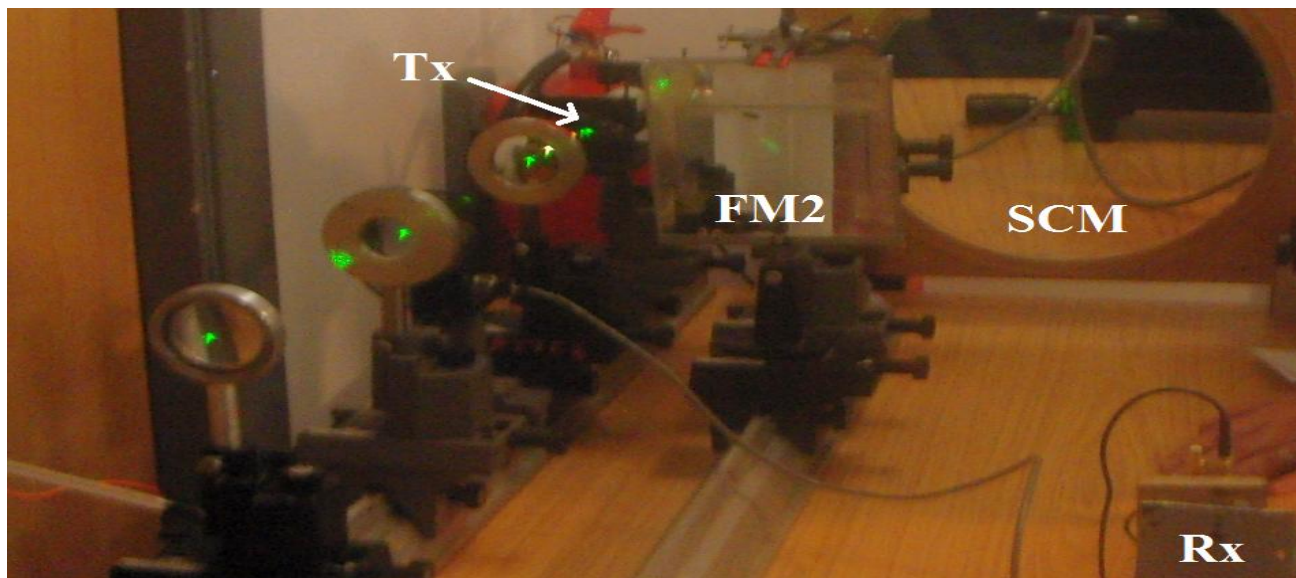
FSO Turbulence – Measurement – Optical Intensity Fluctuation

$$p(I) = \frac{1}{\sqrt{2\pi\sigma_I^2}} \frac{1}{I} \exp \left\{ -\frac{(\ln(I/I_0) + \sigma_I^2/2)^2}{2\sigma_I^2} \right\}$$

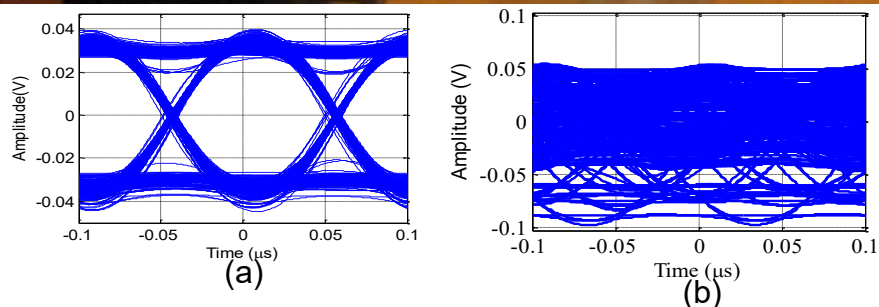


With no turbulence the distribution is **Gaussian**, whereas with turbulence the pdf is best fit to the **log-normal distribution**

FSO Turbulence – Measurement – Optical Intensity Fluctuation

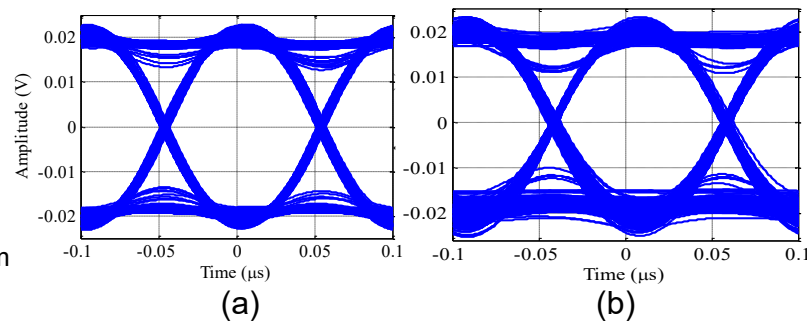


Scattered spot at 104 m due to turbulence @ 633 nm wavelength

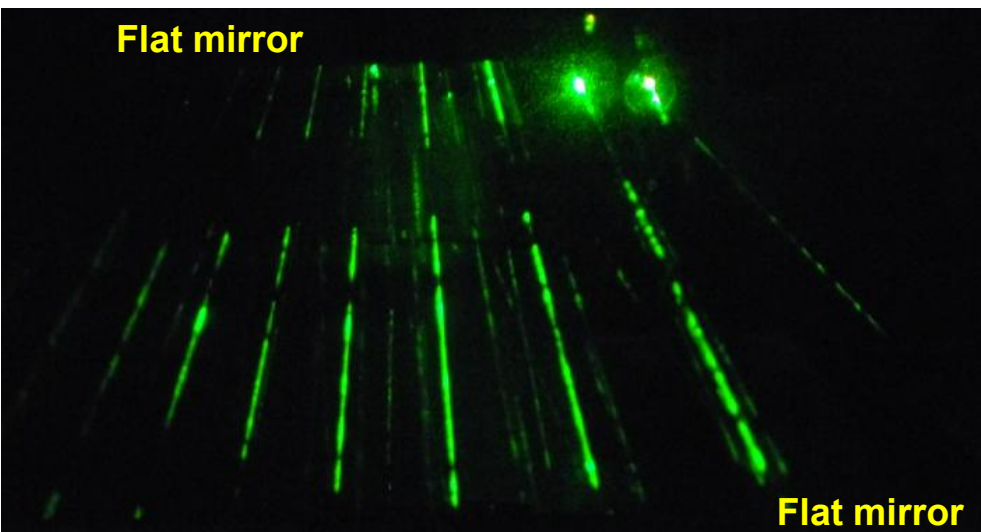
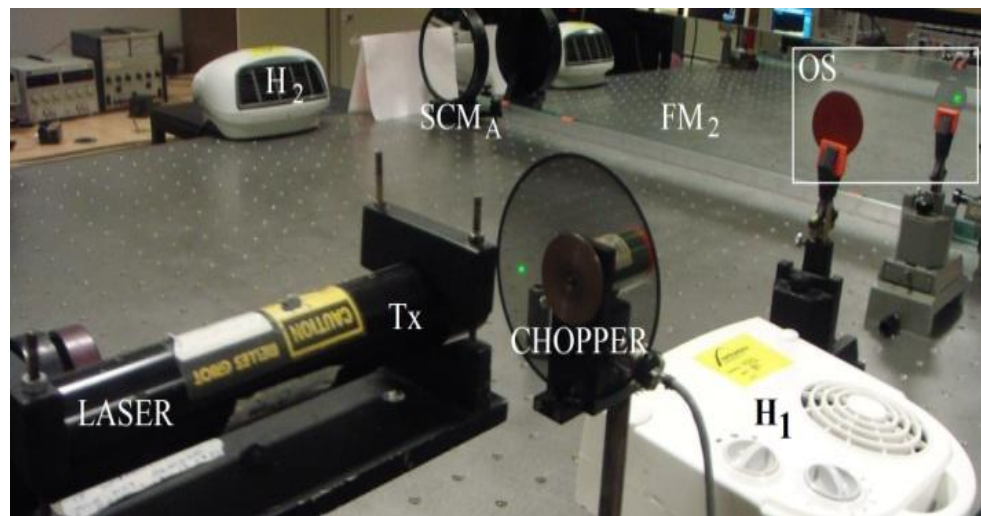


(a) with no turbulence and with no mirror;
(b) with turbulence and with no mirror

(a) with no turbulence and with mirror (i.e., aperture averaging);
(b) with turbulence and with mirror



FSO Turbulence – Measurement – Optical Intensity Fluctuation



| Turbulence | Fan heaters | Lens | | SCM | |
|-----------------------------|---------------------------------|----------|-----------------------------------|----------|-----------------------------------|
| | | Q-factor | σ_I^2 ($\times 10^{-3}$) | Q-factor | σ_I^2 ($\times 10^{-3}$) |
| No | - | 33.37 | 0.0 | 29.12 | 0 |
| Receiver end | H ₂ | 25.37 | 0.4895 | 18.49 | 0.6000 |
| Transmitter end | H ₁ | 24.99 | 0.4993 | 20.59 | 0.8000 |
| Transmitter & receiver ends | H ₁ ; H ₂ | 20.87 | 1.229 | 15.86 | 4.7000 |

Open mirror-based chamber, OCRG

FSO Turbulence – Performance

The average value of SNR is used to evaluate the FSO link performance. The ensemble mean of SNR is:

$$\langle SNR \rangle = \frac{SNR_0}{\sqrt{\sigma_I^2(D)(SNR_0)^2 + \frac{I_0}{\langle I \rangle}}},$$

where SNR_0 is for the turbulence free condition. Therefore, with no turbulence $\langle SNR \rangle = SNR_0$, where $\langle . \rangle$ denotes the ensemble average.

The bit error rate (BER) for the FSO link with intensity modulation/direct detection (IM/DD) using OOK, under the turbulence condition is calculated as:

$$BER = Q(\sqrt{SNR})$$

where $Q(\cdot)$ is the Gaussian-Q function defined as:

$$Q(y) = \frac{1}{\sqrt{2\pi}} \int_y^\infty \exp\left(-\frac{t^2}{2}\right) dt .$$

FSO Turbulence – Performance

The average BER can be determined by averaging over the PDF of the channel state h :

$$P_e = \int_0^{\infty} f_h(h) Q\left(\sqrt{SNR(h)}\right) dh .$$

The
instantaneous
capacity

$$C(SNR(h)) = \sum_{x=0}^1 P_X(x) \int_{-\infty}^{+\infty} f(y|xh) \times \log_2 \left[\frac{f(y|xh)}{\sum_{m=0,1} f(y|x = mh) P_X(m)} \right] dy$$

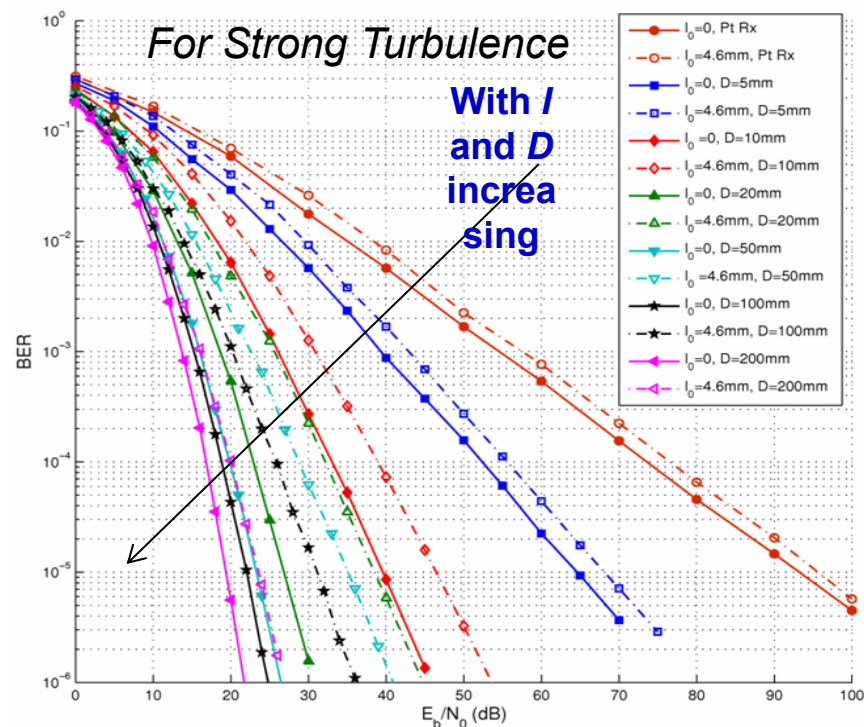
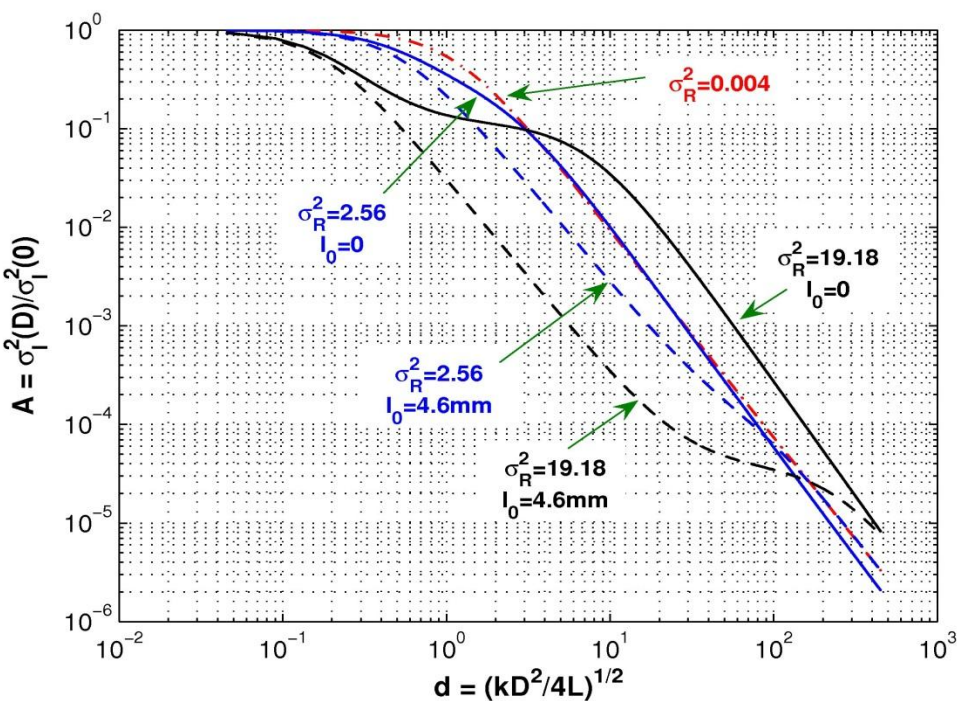
$P(x)$ is the probability of the bit being one ($x = 1$) or zero ($x = 0$), with $P_X(x = 0) = P_X(x = 1) = 0.5$, and $f(y|x, h)$ can be expressed as:

$$f(y|x, h) = \begin{cases} \frac{1}{\sqrt{2\pi\sigma_n^2}} \exp\left[-\frac{y^2}{2\sigma_n^2}\right], & x = 0 \\ \frac{1}{\sqrt{2\pi\sigma_n^2}} \exp\left[-\frac{(y - 2P_{FSO}\gamma h)^2}{2\sigma_n^2}\right], & x = 1. \end{cases}$$

1- J.-B. Wang, M. Sheng, X. Song, Y. Jiao, and M. Chen, "Comments on `BER performance of FSO links over strong atmospheric turbulence channels with pointing errors," IEEE Commun. Lett., vol. 16, pp. 22-23, Jan. 2012; 2- H. G. Sandalidis, T. A. Tsiftsis, G. K. Karagiannidis, and M. Uysal, "BER performance of FSO links over strong atmospheric turbulence channels with pointing errors," IEEE Commun. Lett., vol. 12, pp. 44-46, Jan. 2008; 3- A. K. Majumder, "Free-space laser communication performance in the atmospheric channel," in Free-Space Laser Communications: Principles and Advances A. K. Majumder and J. C. Ricklin, Eds., ed New York, NY: Springer-Verlag, 2008, pp. 57-108.

FSO Turbulence – Mitigating Effect

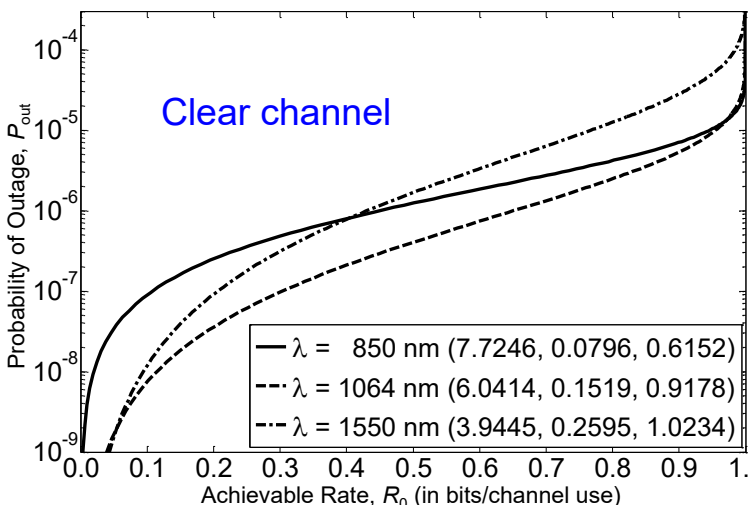
Aperture averaging



FSO Turbulence – Performance

- Optical slow-fading channel is random and remains unchanged over a long block of bits → the time-varying channel capacity C is not sufficient to support a maximum data rate when the instantaneous SNR falls below a threshold [1]. This is known as system outage → resulting in a loss of potentially up to 10^9 consecutive bits at a data rate of 10 Gbps, under deep fades scenarios that may last for ~1-100 ms [2].
- So, the **outage probability** is used as the performance measure of capacity, where the probability that the instantaneous C falls below a transmission rate R_0 :

$$P_{\text{out}} = \text{Prob}(C(\text{SNR}(h)) < R_0).$$



$L = 3.5$ km, $D = 100$ mm, $w_0 = 50$ mm, and $\lambda = \{850, 1064, 1550\}$ mm. Numerical values in the figure legend refers to $(\sigma_I^2(0), A_g, \sigma_I^2(D))$ [3].

1- D. K. Borah and D. G. Voelz, "Pointing error effects on free-space optical communication links in the presence of atmospheric turbulence," J. Lightw. Technol., vol. 27, pp. 3965-3973, Sep. 2009; 2- E. J. Lee and V. W. S. Chan, "Part 1: optical communication over the clear turbulent atmospheric channel using diversity," IEEE J. Sel. Areas Commun., vol. 22, pp. 1896-1906, Nov. 2004; and 3- I. E. Lee, Z. Ghassemlooy, W. P. Ng and M. Uysal, "Performance analysis of free space optical links over turbulence and misalignment induced fading channels," 2012 8th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP), Poznan, Poland, 2012, pp. 1-6, doi: 10.1109/CSNDSP.2012.6292668.

FSO Turbulence – Mitigating Effect

Mitigating channel fading

Time, Polarization and Wavelength Diversities

- Moderate to strong turbulence regimes
- Long link distances

Space Diversity

- Multiple beam FSO system (MISO)
- Multiple aperture FSO system (SIMO)
- Multiple beam, multiple aperture FSO system (MIMO)

Adaptive Optics

Using diformable mirrors

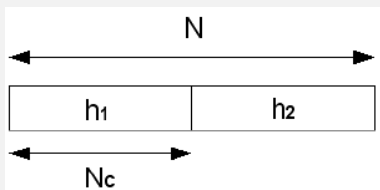
Focusing System

Using scalable free forms

FSO Turbulence – Mitigating Effect

• Time diversity

- Sending a frame several times with long enough interval between them
- Experiencing different fading conditions



• Time diversity & channel coding

- Introducing redundancy
- Using long-enough interleavers
- Better bandwidth efficiency
- Need to long interleavers:
 - Large delay latencies, huge amount of memory
 - E.g.: $\tau_c = 10\text{ms}$, 1Gbps OOK \Rightarrow each fading block: 10^7 bits!

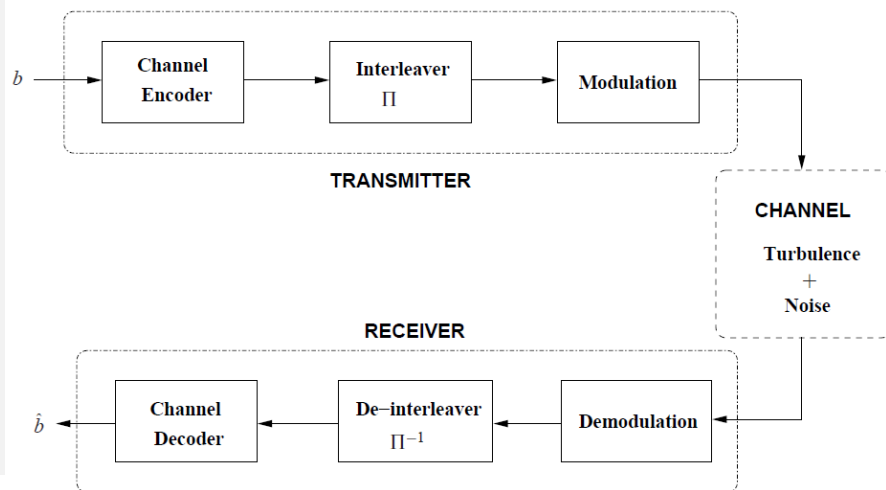
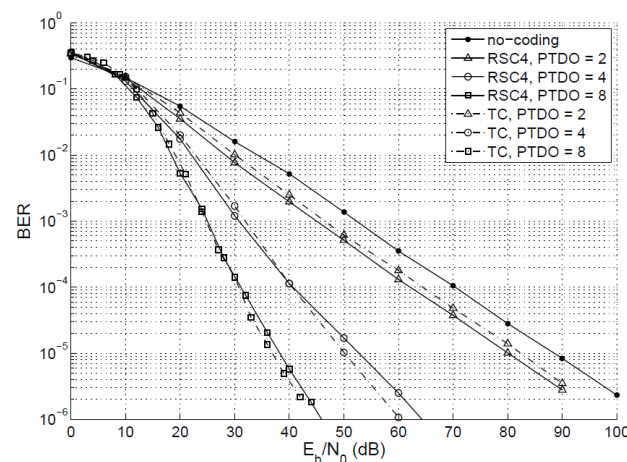


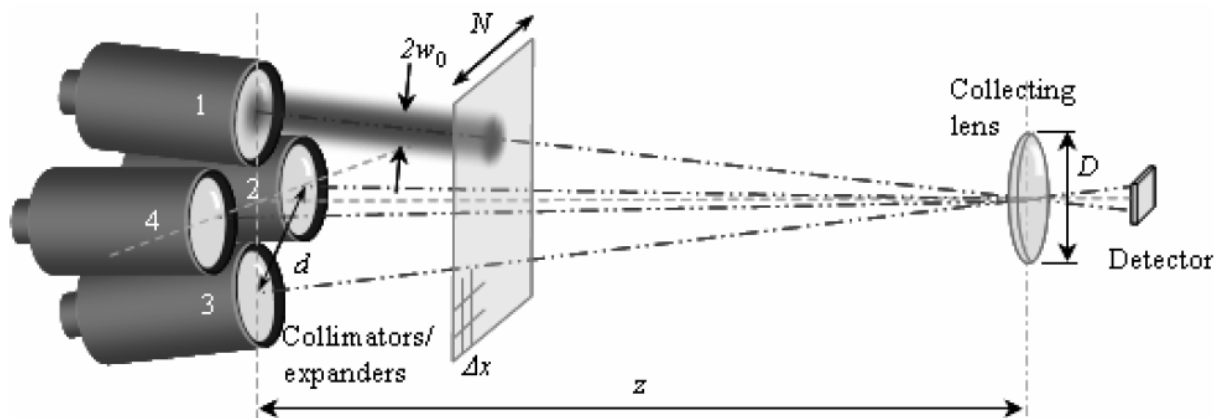
Fig. 1. System block diagram.



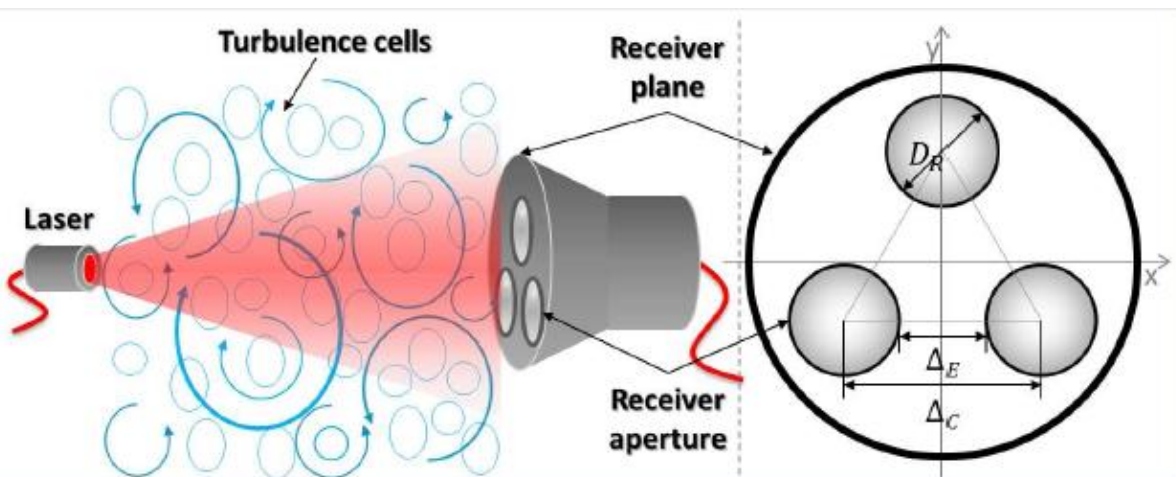
FSO Turbulence – Mitigating Effect

Space diversity

MISO



SIMO

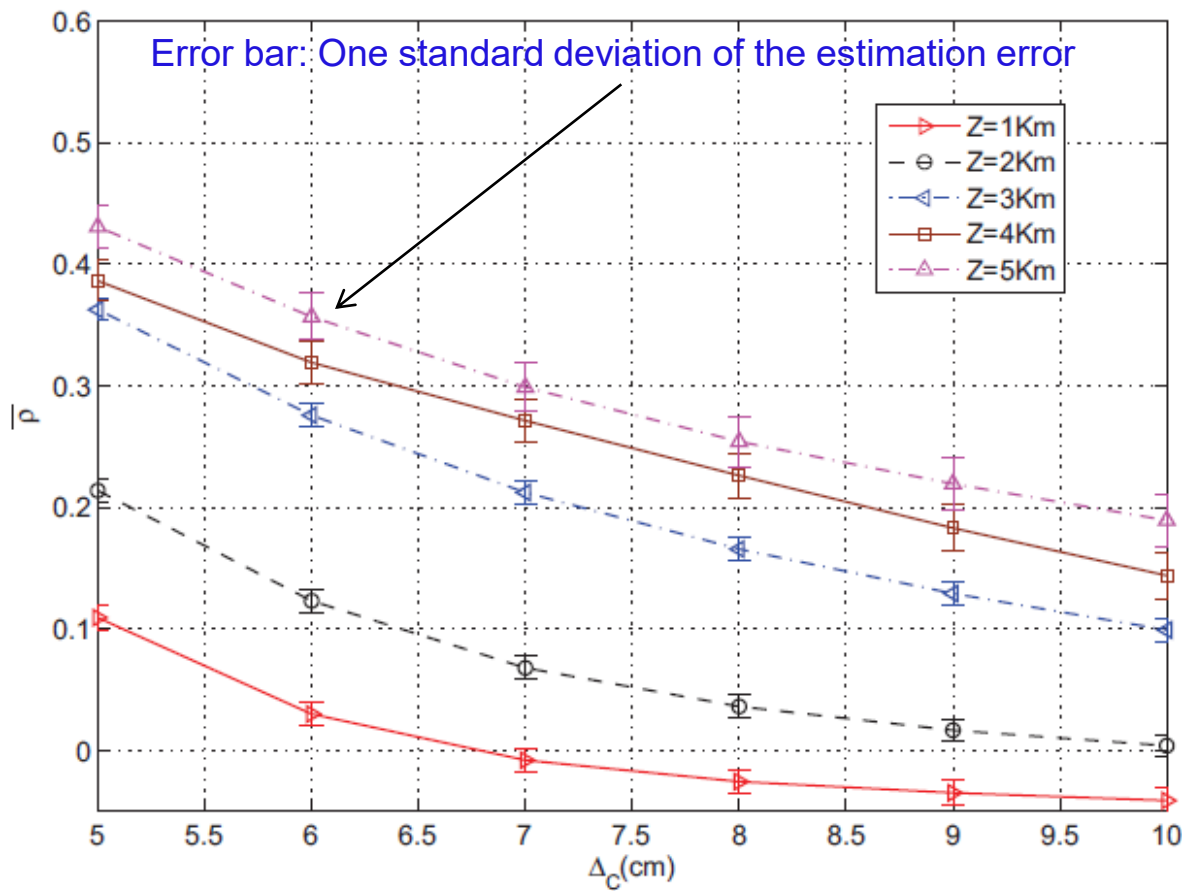


- Aperture diameter D_R , center separation Δ_C , edge separation Δ_E
- Channel coefficient $H_i = \frac{I_{R_i}}{I_T}$, I_T : transmitted intensity, I_{R_i} : received intensity on the i -th aperture
- Correlation coefficient $\rho_{ij} = \frac{\text{Cov}(H_i, H_j)}{\sqrt{\text{Var}(H_i)\text{Var}(H_j)}}$

SPIE Conferenc eProceedings Vol. 6304 2006, Multi-Beam Space-Time Coded Systems for Optical Atmospheric Channels, J. A. Anguita, M. A. Neifeld, and B. V. Vasic.

Yang, G., Khalighi, M.A., Bourennane, S., Ghassemlooy, Z.: 'Fading correlation and analytical performance evaluation of the space-diversity free-space optical communications system', IOP J. Opt., 2014, 16, (3), pp. 1–10

FSO Turbulence – Mitigating Effect

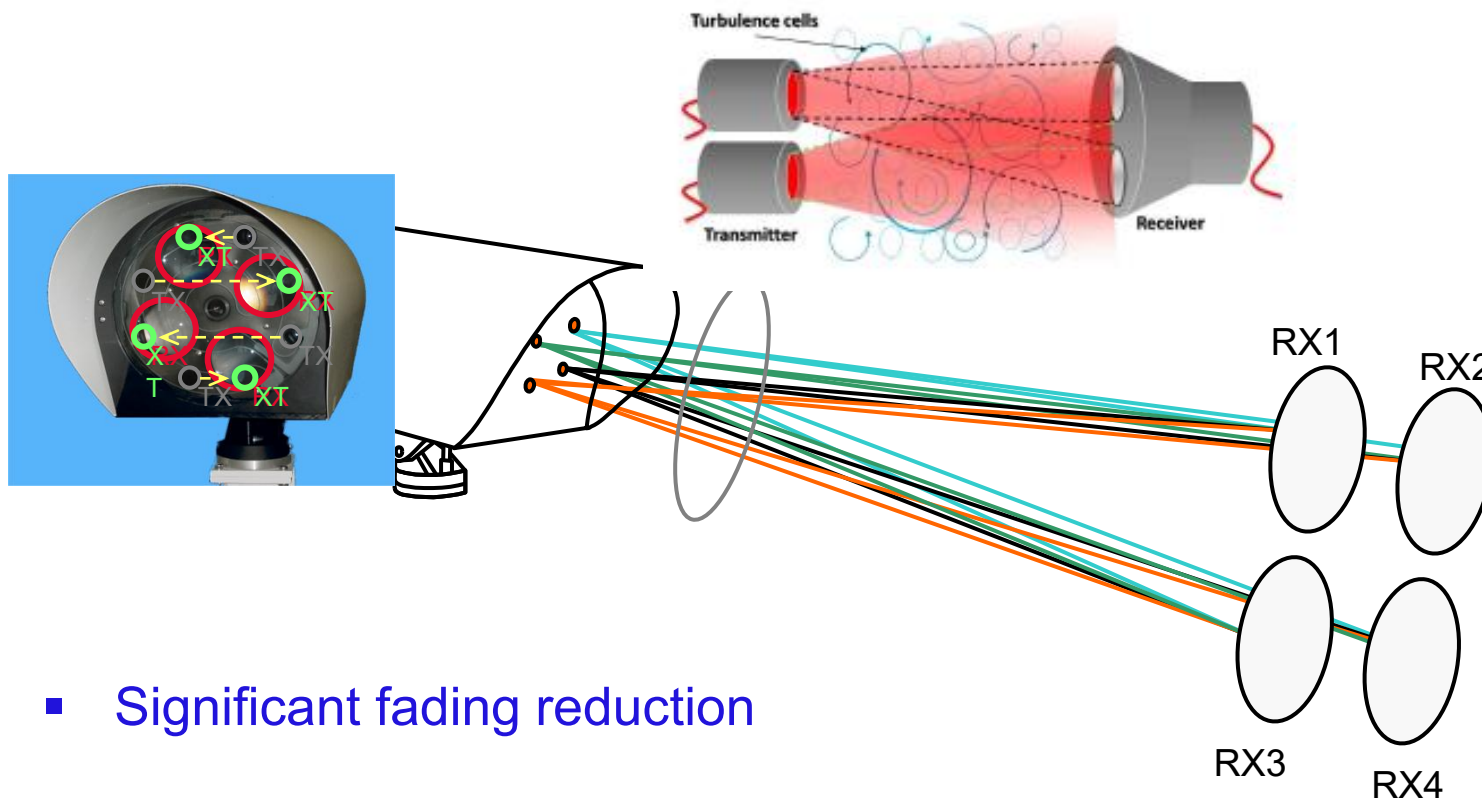


SIMO

Correlation coefficient
 $D_R = 5\text{cm}$

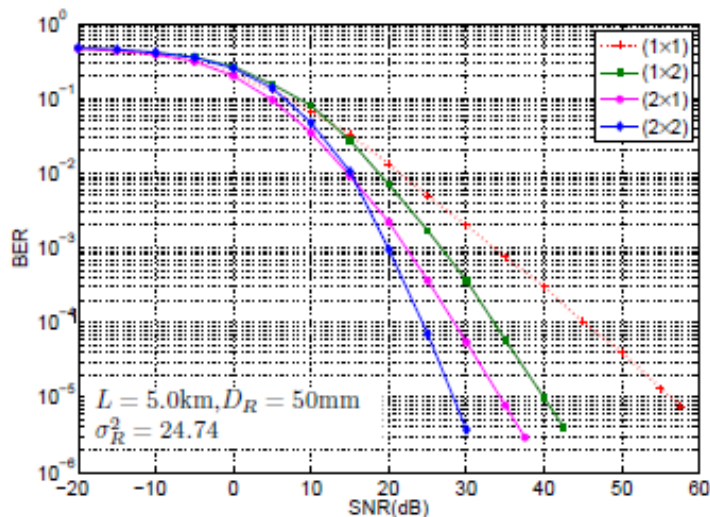
- For all cases, $\rho \downarrow$ with $\Delta_c \uparrow$
- For a fixed Δ_c , $\rho \uparrow$ with Z

FSO Turbulence – Mitigating Effect



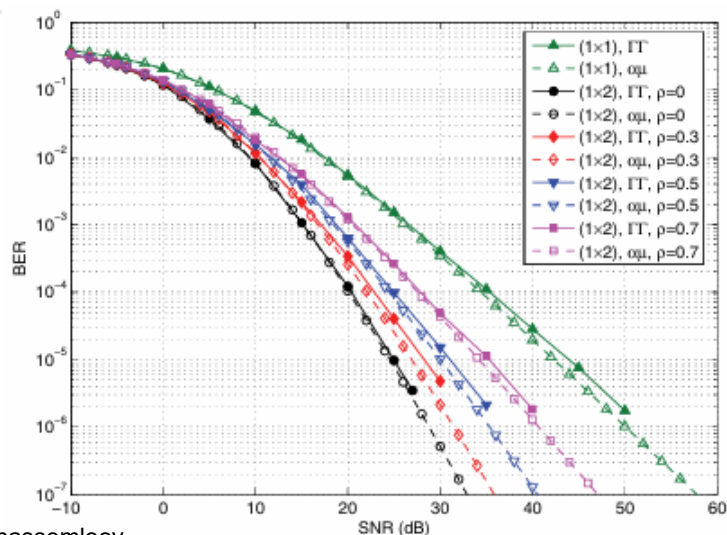
- Significant fading reduction
- Signal transmission schemes:
 - Space-time (ST) coding
 - Trade-off between multiplexing and diversity gains

FSO Turbulence – Mitigating Effect



(1 x 1) – worst
(2 x 2) – best

- Equal gain combining
- Same average transmit optical power
- Fixed total receiver aperture size
- OOK
- PIN photodetector
- Independent fading



Solid lines - Simulated data using Gamma-Gamma $\Gamma\Gamma$ model

Dashed lines - Analytical BER using α - μ approximation model.

$Z = 5\text{ Km}$, $D = 100\text{ mm}$.

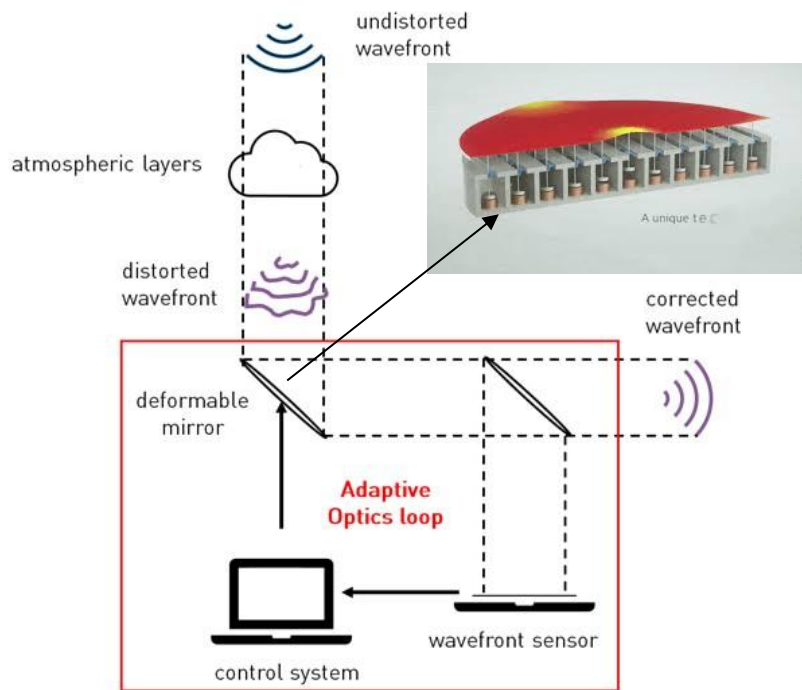
Uncoded OOK.

Background noise limited receiver.

G. Yang, M. -A. Khalighi, S. Bourennane and Z. Ghassemloooy, "Approximation to the Sum of Two Correlated Gamma-Gamma Variates and its Applications in Free-Space Optical Communications," in IEEE Wireless Communications Letters, vol. 1, no. 6, pp. 621-624, December 2012, doi: 10.1109/WCL.2012.091312.120469.

FSO – Mitigating Turbulence

Adaptive Optics (AO) - Measuring wavefront distortions and applying real-time corrections using deformable mirrors (DMs). Pre-distortion AO improves the efficiency of optical coupling, even at low elevation angles (in ground-to-satellite links) where the atmospheric path is longest. It can also reduce the power loss by 30-35 dB.



Key items:

- DM - used to compensate for the scintillation induced distortion.
- The control system - Computes the commands for the DM.
- A wavefront sensor – The key item that give an instantaneous picture of the incoming wavefront. It measures the deviation from an undistorted wave.
- Real-time

FSO – Mitigating Turbulence

In space communication to achieve much higher data rates i.e., > 100+ Gbps range a tip/tilt AO stabilisation scheme for coherent link is needed to:

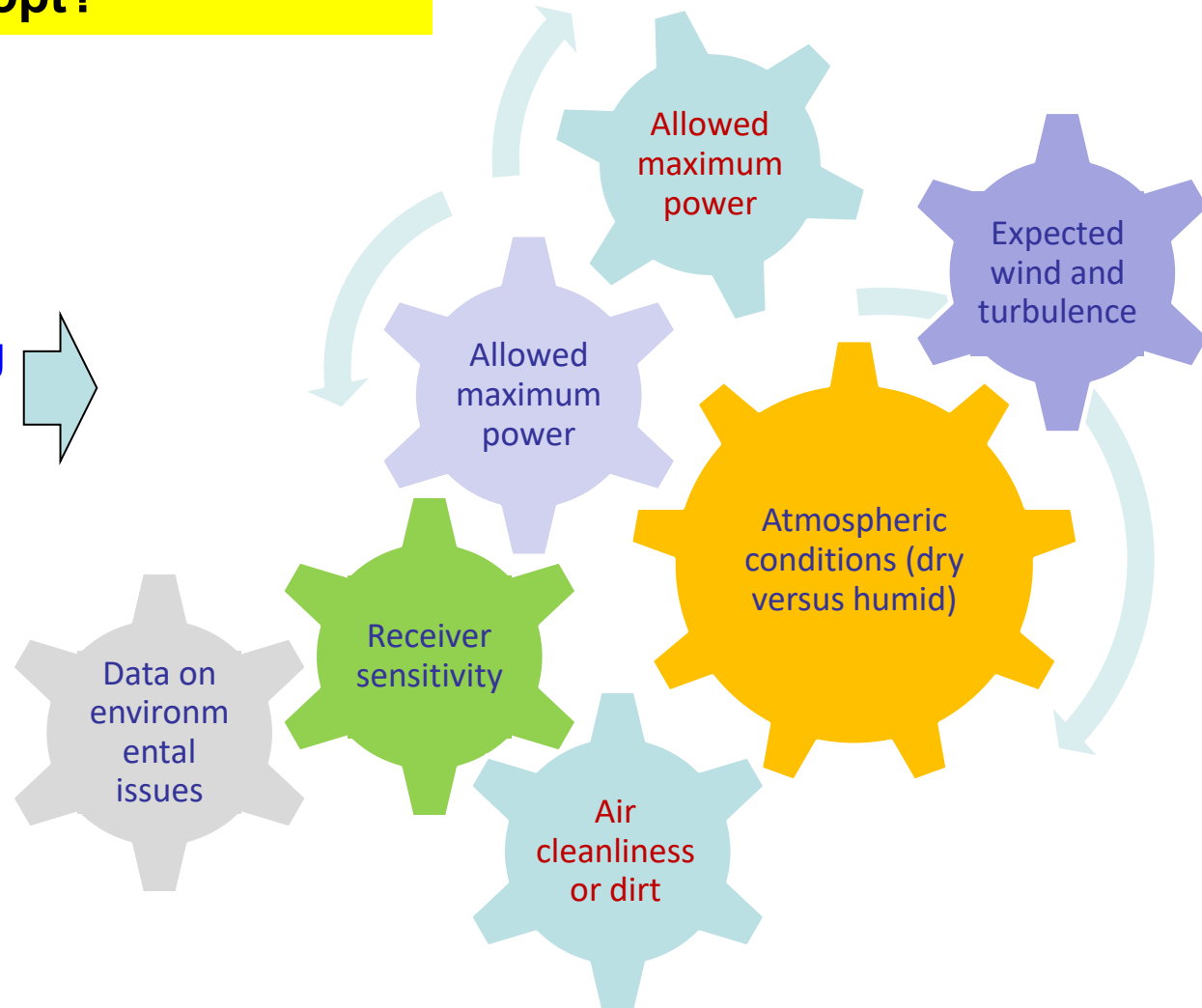
- improve downlink single mode fibre coupling efficiency
- pre-compensate uplink beam wander.

Walsh, S.M., Karpathakis, S.F.E., McCann, A.S. et al. Demonstration of 100 Gbps coherent free-space optical communications at LEO tracking rates. *Sci Rep* 12, 18345 (2022). <https://doi.org/10.1038/s41598-022-22027-0>; Chen, C. et al. Demonstration of a bidirectional coherent air-to-ground optical link. In *Free-Space Laser Communication and Atmospheric Propagation XXX* Vol. 10524 (eds Hemmati, H. & Boroson, D. M.) 120–134 (International Society for Optics and Photonics SPIE, 2018). <https://doi.org/10.1117/12.2292848>

FSO – Mitigating Turbulence

Which approach to adopt?

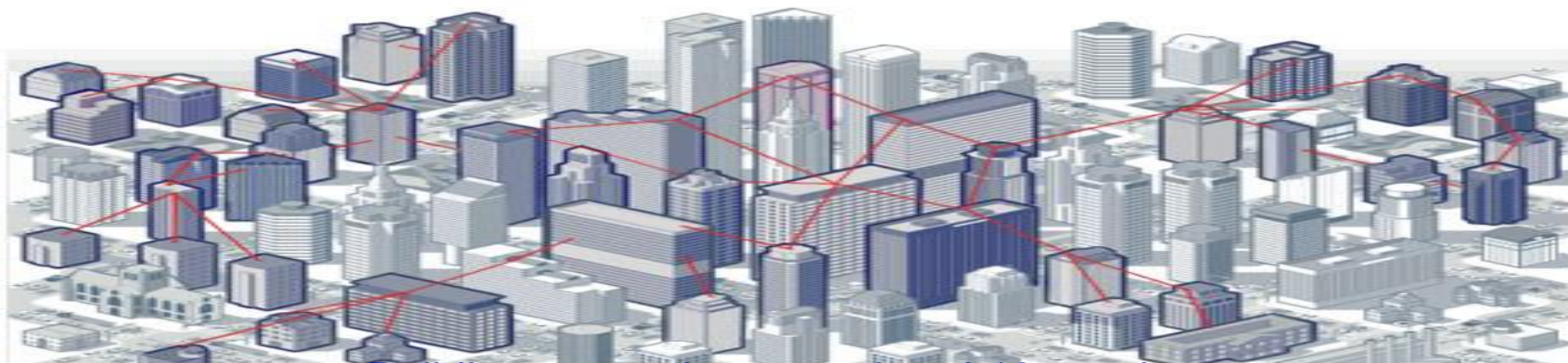
By means of modelling taking into consideration:



FSO – Pointing Error

FSO Challenges - Physical Obstructions

Pointing Stability and Swaying Buildings



Buildings move between 4 and 10 mrad

| Effects | Solutions | Remarks |
|--|---|--|
| <ul style="list-style-type: none"> ■ Loss of signal ■ Multipath induced Distortions ■ Low power due to beam divergence and spreading ■ Short term loss of signal | <ul style="list-style-type: none"> ■ Spatial diversity ■ Mesh architectures: using diverse routes ■ Ring topology: User's n/w become nodes at least one hop away from the ring ■ Fixed tracking (short buildings) ■ Active tracking (tall buildings) | <ul style="list-style-type: none"> ■ May be used for urban areas, campus etc. ■ Low data rate ■ Uses feedback |

FSO – Pointing and Stability

- **Pointing error**
 - Due to the building sway at the transmitter and receiver
 - Occur along with a boresight error, which causes a deterministic displacement of the laser beam at the receiving aperture.
 - The boresight errors are more pronounced in the longer distance FSO communication systems like in earth-to-satellite links.

- **Pointing accuracy**
 - Is critical in FSO than Rf due to the narrow beam divergence in FSO ($\sim 10X$ < RF signals) [1].
 - Typically, on the order of several hundred μrad
 - So, steering mechanisms may be required.

- **Algorithms - Carefully tailored to better locate and receive the faint and narrow signals.**

[1] F. Yang, et al, "Free-space optical communication with nonzero boresight pointing errors," *IEEE Trans. Commun.*, 62,, 2, pp. 713–725, Feb. 201; Kaushal, H. and Kaddoum, G. (2015). Free Space Optical Communication: Challenges and Mitigation Techniques. *IEEE Communications Surveys & Tutorials*, 19(1), 57 - 96. DOI: 10.1109/COMST.2016.2603518; M. T. Dabiri, S. M. S. Sadough, and M. A. Khalighi, "Blind signal detection under synchronization errors for FSO links with high mobility," *IEEE Transactions on Communications*, vol. 67, no. 10, pp. 7006–7015, 2019; X. Liu, "Free-space optics optimization models for building sway and atmospheric interference using variable wavelength," *IEEE Transactions on Communications*, vol. 57, no. 2, pp. 492–498, 2009.

FSO – Pointing and Stability

Pointing Errors (PEs)

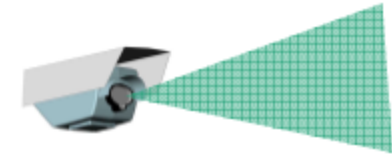
| Type | Cause | Magnitude | Frequency |
|-----------|--------------------------------|-----------|----------------------------|
| Tip/tilt | Thermal expansion | High | Once per day |
| Away | Wind | Medium | Once every several seconds |
| Vibration | Equipment, door slamming, etc. | Low | Many times per second |

Kaushal, H. and Kaddoum, G. (2015). Optical Communication in Space: Challenges and Mitigation Techniques. *IEEE Communications Surveys & Tutorials*, 19(1), 57 - 96. DOI: 10.1109/COMST.2016.2603518; M. T. Dabiri, S. M. S. Sadough, and M. A. Khalighi, "Blind signal detection under synchronization errors for FSO links with high mobility," *IEEE Transactions on Communications*, vol. 67, no. 10, pp. 7006–7015, 2019; X. Liu, "Free-space optics optimization models for building sway and atmospheric interference using variable wavelength," *IEEE Transactions on Communications*, vol. 57, no. 2, pp. 492–498, 2009.

FSO – PEs - Solutions

Short range FSO

- Increased beam divergence
- Geometric power loss



2 – 10 mrad divergence
= 2 to 10 meter spread at 1 km

Long range FSO

- Very low beam divergence
- Automatic tracking mechanism:
Increased cost & complexity



0.2 – 1 mrad divergence
= 0.2 to 1 meter spread at 1 km

FSO – MIMO with Turbulence and PEs

- MIMO wireless communication system is a well-established technology, known for improved capacity; better diversity gain; and Increased coverage area [1]–[3].
- The **GG distribution** is represented in terms of the **modified Bessel function of the second kind**, and therefore, **it is very challenging and complicated to analyze** the performance of a general FSO MIMO system.
 - In [4] a **power series representation** of the modified Bessel function is used to approximate error rate of the binary modulation for
 - **equal gain combining (EGC)**
 - **maximal ratio combining (MRC)** over the GG fading AT.

FSO – MIMO with Turbulence and PEs

- The power series representation of the GG probability density function, is used to obtain the average bit error rate of the Alamouti spacetime block coded [1] for 2×1 FSO system.
- In [2], analytical approach has been adopted to eventuate the performance of space-diversity FSO links over correlated GG fading channels.

FSO – MIMO with Turbulence and PEs

■ Mitigation Schemes

- **Broadening the optical beam** but at the cost of received power level (i.e., reduced signal-to-noise ratio (SNR) and increased error rate) and the security breach.
 - This approach is necessary when establishing links with moving platforms
- **A narrow optical beam and multiple receive apertures** (i.e., receive diversity).
 - Narrowing of the optical beam reduces the geometrical losses and increases the FSO link security but at the cost of increased misalignment.
- **Acquisition, tracking, and pointing (ATP)** – Deals with alignment by dynamically adjusting beam direction to compensate for platform vibration, PE, and beam wander [2].
- A statistical channel model for FSO MIMO. Showing that **diversity order is determined by PE effects** other than the number of Tx's or Rx's.

FSO – MIMO with Turbulence and PEs

- Meijer-G function-based PDF expression of the GG fading FSO links with PEs poses a significant challenge for deriving the analytical performance of a generalized FSO MIMO system. Thus, it is difficult to theoretically study the effect of the PEs in a FSO MIMO over different SNR range.
- **Therefore, EGC and MRC schemes in the GG fading FSO links with PEs.**
 - Subcarrier intensity modulation scheme with M-array PSK
 - Developed a power series expansion of the Meijer-G function,
 - Using the series manipulations, obtained the average BER of the EGC and MRC
 - The analysis sheds substantial light on the asymptotic properties of FSO MIMO in presence of the PEs;
 - Show that the asymptotic attributes—diversity and combining gain—are dominated by PEs if they are more hostile than the AT.

FSO – MIMO with Turbulence and PE

- The asymptotic value of the BER can be expressed in terms of combining gain (G_c) and diversity gain (G_d). as:

$$Pe(\gamma) \approx (G_c \gamma)^{-G_d}$$

$$Pe(\gamma) = \zeta_M \frac{\Xi_0^{\text{EGC}}(\mathbf{k}_{G_d}) (\sqrt{2}/a_1)^{2G_d}}{\gamma^{G_d} 2G_d \sqrt{\pi}} \Gamma\left(\frac{2G_d + 1}{2}\right)$$

where

$$\Xi_0^{\text{EGC}}(\mathbf{k}_{G_d}) = \frac{M^{G_d} C_0(\mathbf{k}_{G_d})}{2\Gamma(2G_d)}$$

$$Pe(\gamma) = \zeta_M \sum_{\substack{\sum_{k_1=0}^N \sum_{k_2=0}^{N-k_1} j_{k_1, k_2, N-k_1-k_2} \\ 0 \leq j_{k_1, k_2, N-k_1-k_2} \leq M}} \binom{M}{j_{k_1, k_2, N-k_1-k_2} \mid \substack{0 \leq k_1 \leq N \\ 0 \leq k_2 \leq N-k_1}} \times \frac{\Xi_0^{\text{MRC}} \left(j_{k_1, k_2, N-k_1-k_2} \mid \substack{0 \leq k_1 \leq N \\ 0 \leq k_2 \leq N-k_1} \right)}{\gamma^{\sum_{k_1=0}^N \sum_{k_2=0}^{N-k_1} j_{k_1, k_2, N-k_1-k_2} (k_1 \xi^2 + k_2 \alpha + (N-k_1-k_2)\beta)}} \times \frac{(\sqrt{2}/a_1)^{\sum_{k_1=0}^N \sum_{k_2=0}^{N-k_1} j_{k_1, k_2, N-k_1-k_2} (k_1 \xi^2 + k_2 \alpha + (N-k_1-k_2)\beta)}}{(\sum_{k_1=0}^N \sum_{k_2=0}^{N-k_1} j_{k_1, k_2, N-k_1-k_2} (k_1 \xi^2 + k_2 \alpha + (N-k_1-k_2)\beta)) \sqrt{\pi}} \times \Gamma\left(\frac{\sum_{k_1=0}^N \sum_{k_2=0}^{N-k_1} j_{k_1, k_2, N-k_1-k_2} (k_1 \xi^2 + k_2 \alpha + (N-k_1-k_2)\beta) + 1}{2}\right)$$

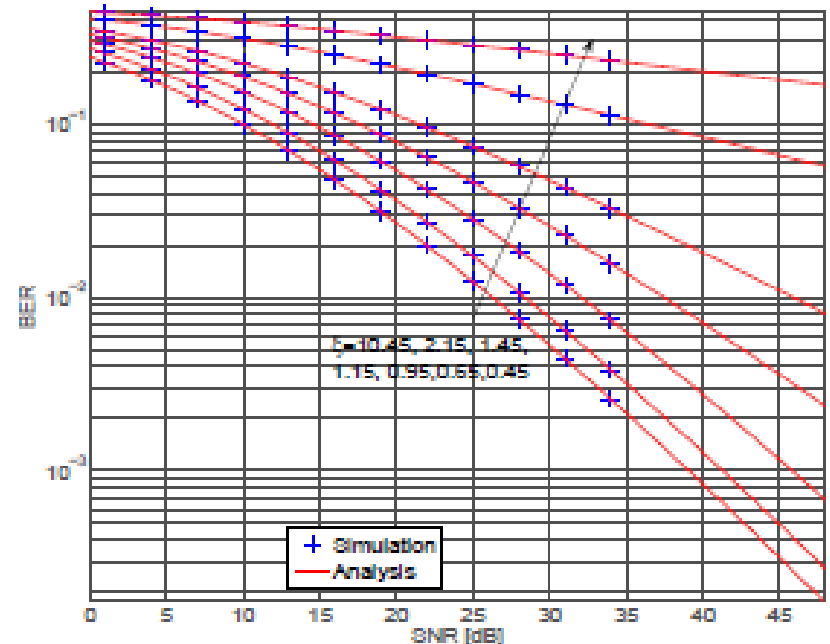
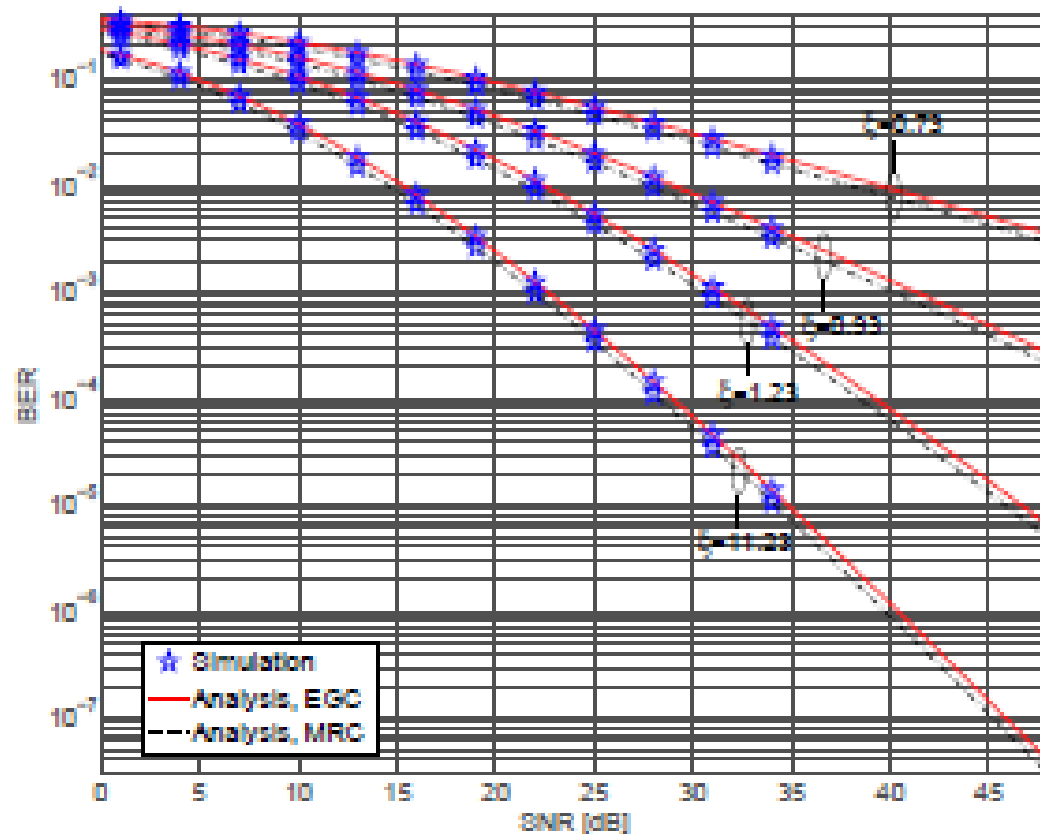


Fig. 1. BER versus SNR performance of the FSO system with $N = M = 1$, QPSK, GG fading with PEs, $\alpha = 2.1$, $\beta = 2$, $\xi = 10.45, 2.15, 1.45, 1.15, 0.95, 0.65, 0.45$, and $A_0 = 1$.

- Close match between simulated and predicted BER for all values and PEs
- Decreasing value of ξ denotes increasing severity of PEs.
- For large PEs, i.e., $\xi = 0.45$, the FSO system becomes almost useless

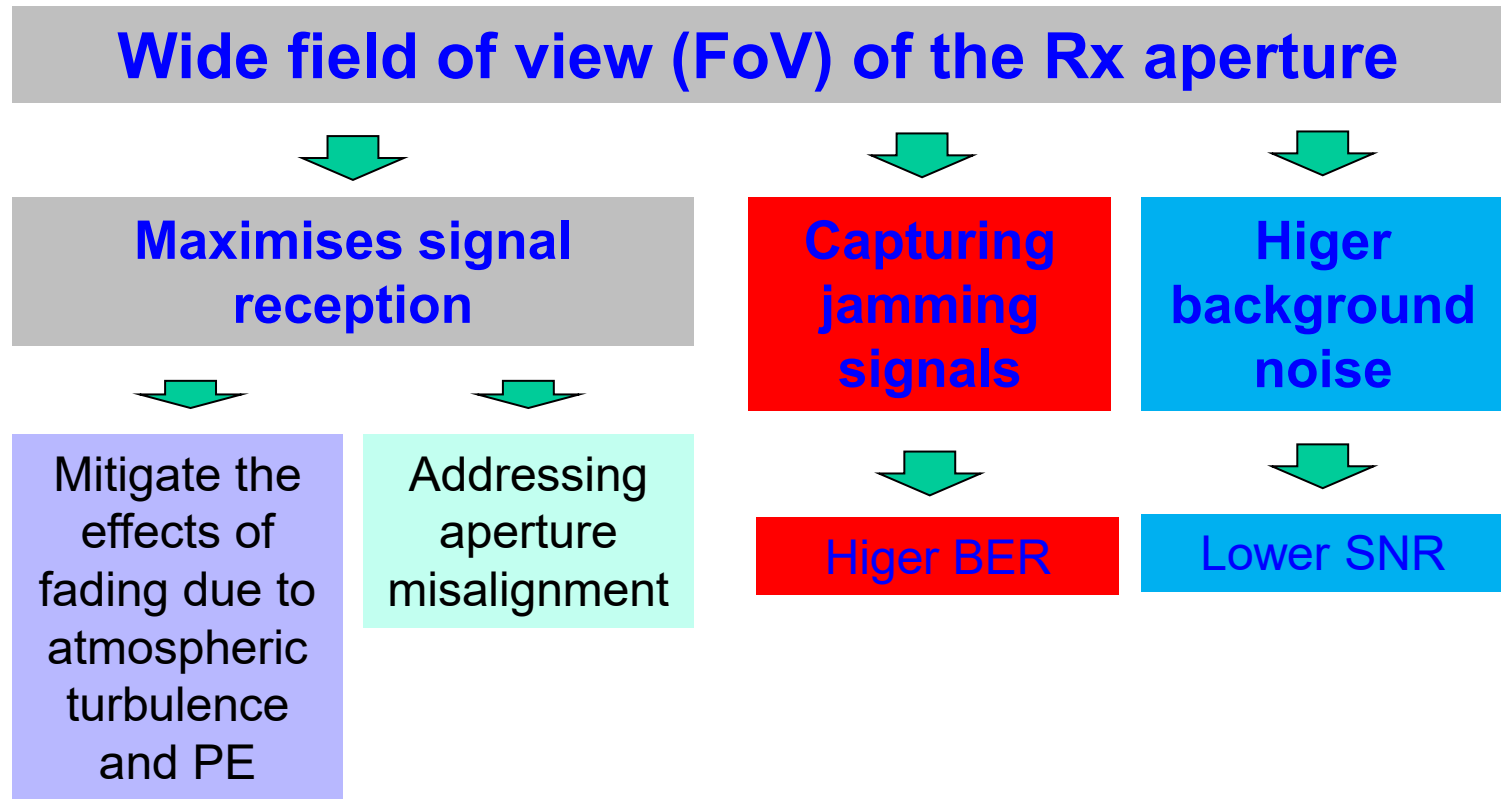
FSO – MIMO with Turbulence and PE

- MRC provides slight performance gain as compared to EGC.
- At $BER=10^{-3}$, SNR gain is ~ 0.5 dB and 1 dB at PEs = 11.23 and $\xi = 0.93$, respectively, for MRC.
- PEs indistinguishably affect the performance of MRC and EGC.
- Significant reduction in the performance is observed for $\xi = 1.23, 0.93, 0.73$, as compared to $\xi = 11.23$ case

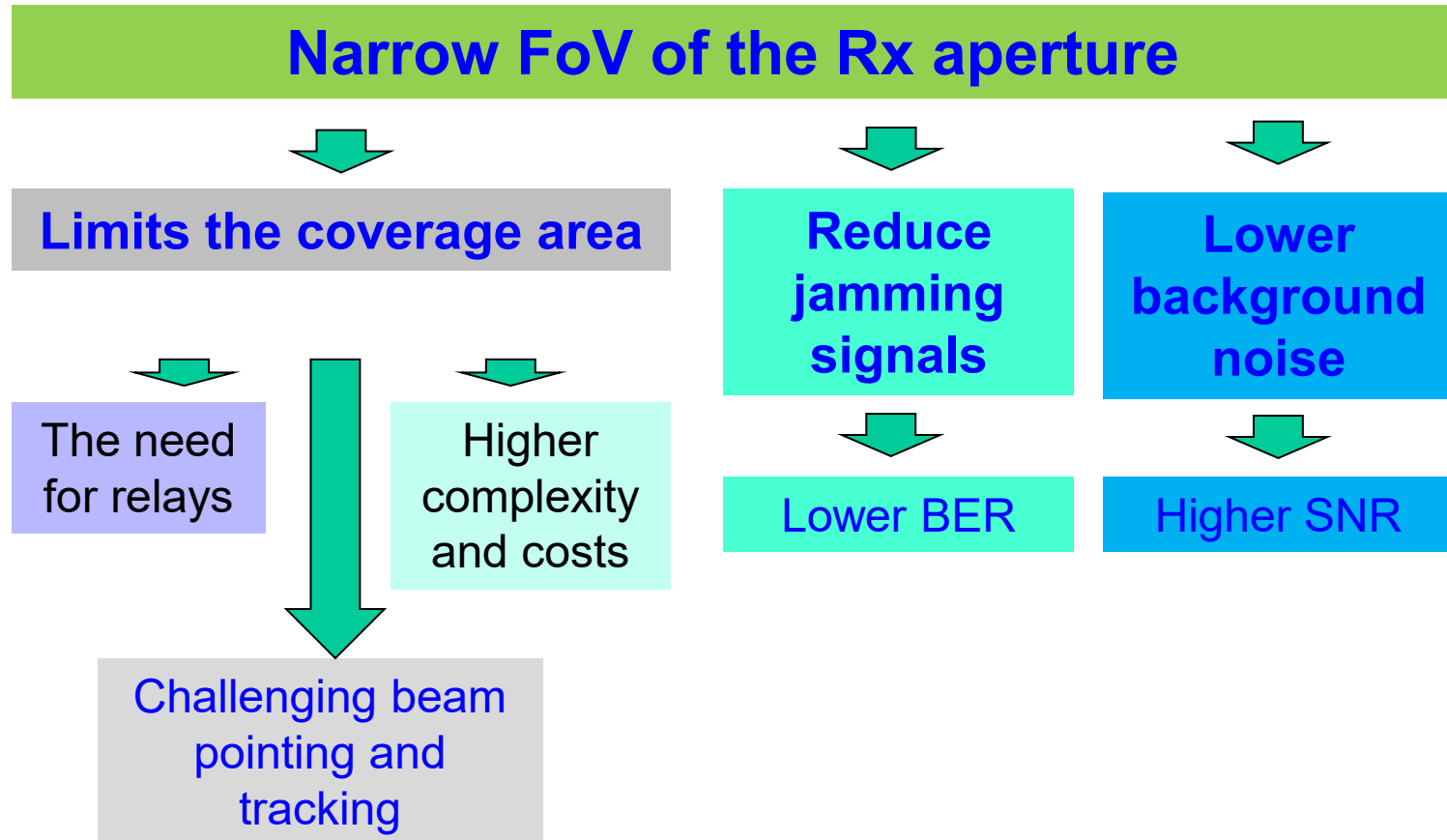


Performance plots of the EGC and MRC schemes in a FSO system with $N = 1, M = 2$, QPSK, GG fading moderate AT with PEs, $\alpha = 4.0$, and $\beta = 1.9, A_0 = 0.75$, and $\xi = 11.23, 1.23, 0.93, 0.73$. AT is considered to be moderate

OWC – Additional Challenges - Jamming



OWC – Additional Challenges - Jamming



Final Remarks

- FSO
 - A unified model is needed
 - Considered Turbulence, pointing errors and jaming.
 - Mitigation schemes

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