Theoretical Advances in Optical Wireless Communications

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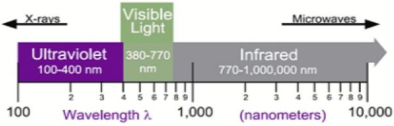
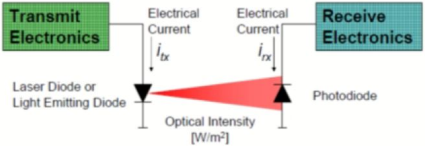
Main Topics

- Optical Wireless: Basics
- Channel Modeling
- Fog Attenuation Modeling
- Coded Modulation for FSO
- Optical Wireless: Information Theory
- Signal Estimation

Optical Wireless Communications (OWC)

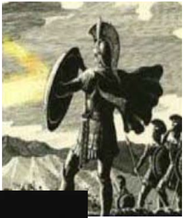
- **OWC:**
  Wireless(unguided)transmission through the deployment of optical frequencies
  - Infrared (IR)
  - Visible (VL)
  - Ultraviolet(UV)
- Intensity Modulation/Direct Detection (IM/DD)
- Amplitude constraints
  - non-negativity of the signal
  - Eye-safety regulations





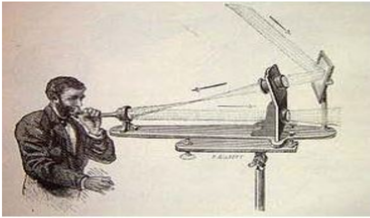
OWC History

- The use of sunlight
  - **Heliograph** (Information delivery using the mirror reflection of sunlight)
- The use of fire or lamp
  - Beacon fire
  - Lighthouse
  - Signal lamp for ship-to-ship communication



OWC History

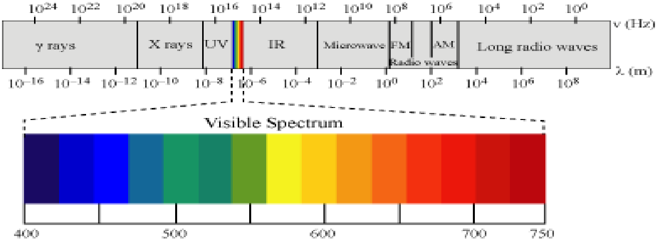
- **A. Graham Bell's "Photophone" (1880)**
  - First wireless phone message
  - Optical Source: Sunlight
  - TX: Vibrating mirror RX: Parabolic mirror
  - Distance: 700 ft (213m)



- In his writings, Bell referred photophone as "**the greatest invention [I have] ever made, greater than the telephone"**.

OWC Advantages

- Large bandwidth capacity
- High degree of spatial confinement
  - High reuse factor
  - Inherent security
  - Lower power requirements
  - Robustness to EMI
- Easy to install and redeployable
- Unregulated spectrum



Present Scenario

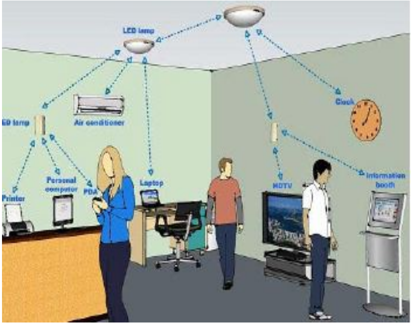
- More mobile phones on this planet than humans
- Approximately over **7.3 billion** mobile phones in the world
  - Spectrum crunch
  - **Possible solution:** Optical Wireless System

Near Future

- **By 2018**
  - Sending the equivalent of **1.8 million** years of HD video every month
- **By 2020**
  - 1000 wireless devices/person
  - Available spectrum will run out
  - As a consequence the energy consumption by base stations will become equivalent to the world air traffic (diesel generators, AC)
- Li-Fi and VLC will grow to be worth over **$100 billion** in next eight years

OWC Integration in 5G Systems

- OWC can provide higher data rates with enhancement
  - Low mobility upto 1Gbps
  - High mobility upto 100 Mbps
- Growing trend: VLC and FSO technologies integration with RF systems
- Boosting of wireless coverage area in indoor systems
- Extensive deployment of 5G mesh optical wireless network
- Unified and programmable infrastructure in 5G promises easy integration of OW links

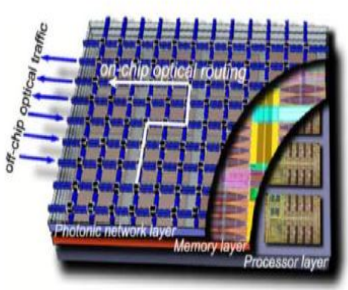


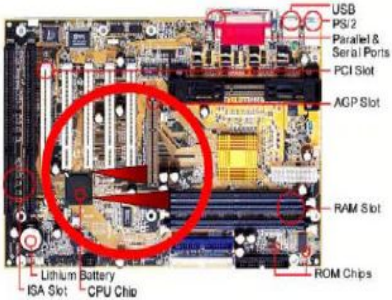
OWC Application Areas

- Depending on the intended application, OWC can serve as a powerful **alternative, complementary or supportive** technology to the existing ones
  - **Ultra-short range** (e.g., optical circuit interconnects)
  - **Short range** (e.g., WBAN,WPAN)
  - **Medium range** (e.g., WLAN, VANET)
  - **Long range** (e.g., inter-building connections)
  - **Ultra-long range** (e.g., Satellite links)

Ultra-Short Range OWC

- on-chip communications
- chip-to-chip communications

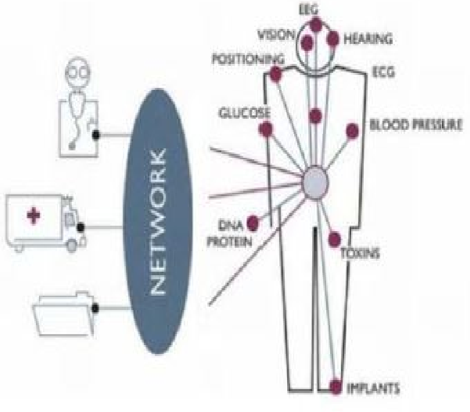




- High-performance computing at the **exaflop** [one quintillion 10^{18} floating operations per second] level

Optical Wireless Body Area Networks (O-WBANs)

- Retrieval of physical and bio-chemical information of the individual through the use of wearable computing devices



Optical Wireless Personal Area Networks (O-WPANs)

- "Last meter" connectivity for interconnecting devices centered around an individual person's workspace
- **infrared Data Association (IrDA)**
  - Giga-IR $\sim$ 1.25 Gb/s
  - 10 Gb/s IR under development

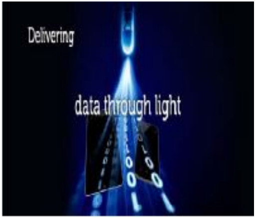
IrReady

Optical Wireless Local Area Networks (O-WLANs)

- **visible light communications**
  - Dual use of lightning for illumination and communication
- **IEEE Standard 802.15.7-2011** "Standard for Short-Range Wireless Communication using Visible Light"
- **Li-Fi Consortium** founded in October 2011
  - http://www.lificonsortium.org/

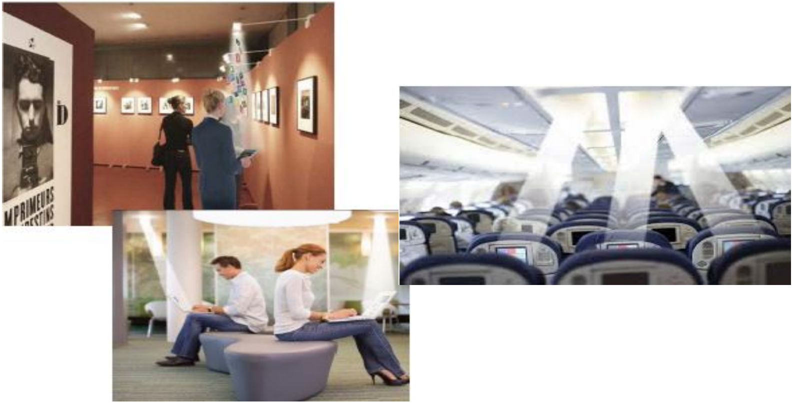
Li-Fi Technology

- Data rate greater than **10 Gbps**; theoretically allowing HD film to be downloaded in 30 seconds, through illuminating LEDs
- Unperceivable high variation in intensity
- Efficient optical version of Wi-Fi
- Tech giant Apple set to include Li-Fi capability in its upcoming iPhone



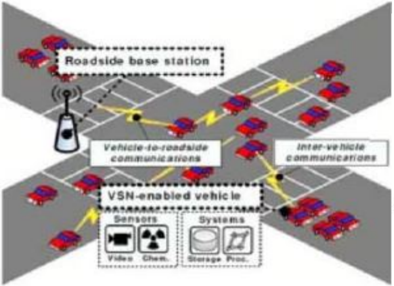
Li-Fi Applications

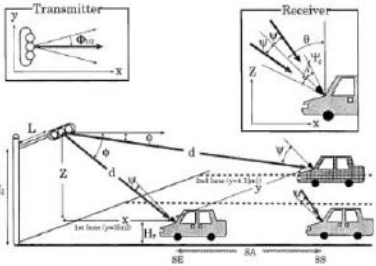
- Augmented reality (e.g., museum, galleries)
- EMI sensitive environment (e.g., aircraft)
- Indoor navigation (e.g., offices)



Optical Vehicular Area Networks (O-VANETs)

- **V2V Communications** via the use of headlights/taillights
- **V2R Communications** via traffic lights, broadcasting displays, etc





Terrestrial OWC Links

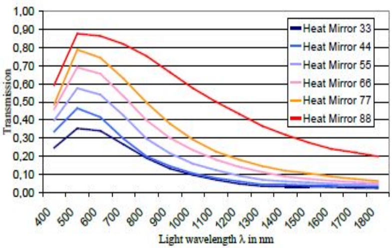
- Atmospheric line-of-sight (LOS) infrared communication also known as **free-space optical (FSO)** communications
  - metropolitan area network (MAN) extension
  - enterprise/campus connectivity
  - optical fibre back-up
  - cellular backhaul and coverage extension
  - wireless video surveillance and monitoring
  - temporary links for disaster recovery and emergency response (e.g., used in recovery efforts after 9/11 NYC)
  - HDTV transmission (e.g., BBC temporary studios in FIFA World Cup 2010)

Ultra-Long Range OWC

- Aircraft uplink/downlink and inter-aircraft link
- High altitude platforms (HAPs) and inter-HAP links
- Satellite communications (e.g., inter-satellite, earth-to-satellite)
- Deep-space links

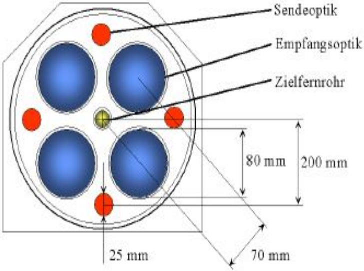
FSO Systems

Type-1 Free Space Optics Systems developed at TU Graz



- FSO systems developed by the research group OptiKom
- Data transmission fully compatible to standard IEEE 802.3i (10 Mbit/s Ethernet, 100 Mbit/s Fast-Ethernet)
- Up to 700 m distance, 2° adjustment angle
- IP67 waterproof RJ45 plug for network and power connection (12V/2A)
- 850 nm technology allowing good transmission through thermally isolated window glass

System Design



Server Free-space optical interconnection (FSOI)

FSOI technology enables ultra high interconnection speed in next-generation servers. FSOIs use laser links between server components and provide a lower bound on propagation delay due to the shortest line-of-sight path and the low index of refraction of air, when compared with the indices common in waveguide technologies. One of the main problems of FSOI systems is the inevitable turbulence effect that results from the air cooling of server components

D. Bykhovsky, D. Elmakias, and S. Arnon, "Experimental Evaluation of Free Space Links in the Presence of Turbulence for Server Backplane," Lightwave Technol. 33, 2923- 2929 (2015).

Dima Bykhovsky and Shlomi Arnon, "OFDM Allocation Optimization for Crosstalk Mitigation in Multiple Free-Space Optical Interconnection Links," J. Lightwave Technol. 33, 2777-2783 (2015).

Multiple Access Resource Allocation in Visible Light Communication Systems

Discrete multi-tone (DMT) modulation is known to be an efficient single-transmitter technique for visible-light communication. However,the use of this technique in a multiple transmitter environment requires effective sub-carrier and power allocation design in order to exploit the full potential of spatial multiple-transmitter diversity. Spatial reuse of the sub-carriers in the presence of interference and power constraints increases the efficiency of multiple access(MA)DMT communication.

Dima Bykhovsky and Shlomi Arnon, "Multiple Access Resource Allocation in Visible Light Communication Systems," J. Lightwave Technol. 32, 1594-1600 (2014).

Dima Bykhovsky and Shlomi Arnon, "An Experimental Comparison of Different Bit-and- Power-Allocation Algorithms for DCO-OFDM," J. Lightwave Technol. 32, 1559-1564 (2014).

Fog Attenuation Measurements

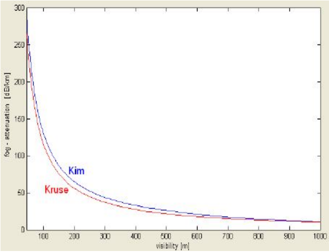
Graz

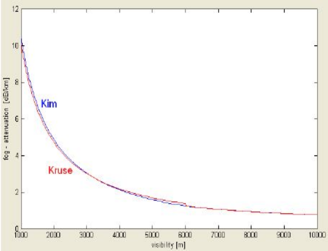
La Turbie (Nice)

Channel Modeling

- Comprehensive Matlab based channel model
- All major atmospheric attenuations/disturbances catered for:
  - Fog
  - Rain
  - Wet/Dry Snow
  - Ambient Sunlight
  - Scintillations

Fog Attenuation





$$\alpha_{spec} = \frac{10 \log V_{\%}}{K[km]} \left(\frac{\lambda}{\lambda_\circ}\right)^{-q} [dB/km]$$

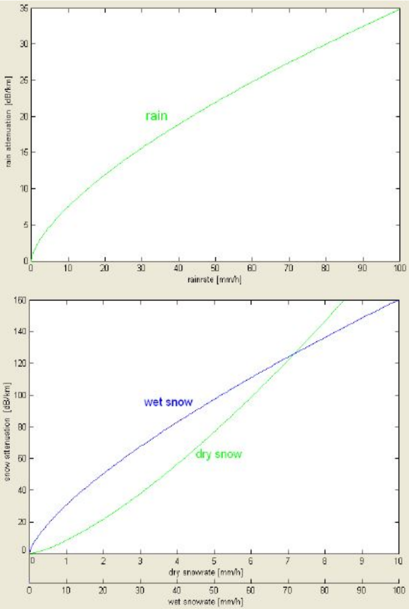
At very high attenuations the Kim model is the better model.

At distances over 6 km both models have the same parameter.

$$Kruse : q = \begin{cases} 1.6 & \textit{if } V > 50km \\ 1.3 & \textit{if } 6km < V < 50km \\ 0.585V^{\frac{1}{3}} & \textit{if } V < 6km \end{cases}$$

$$Kim : q = \begin{cases} 1.6 & \textit{if } V > 50km \\ 1.3 & \textit{if } 6km < V < 50km \\ 0.16V + 0.34 & \textit{if } 1km < V < 6km \\ V - 0.5 & \textit{if } 0.5km < V < 1km \\ 0 & \textit{if } V < 0.5km \end{cases}$$

Rain / Snow Attenuation



$$\alpha_{rain} = 1.076 \cdot R^{\frac{2}{3}} \quad [dB/km]$$

$$\alpha_{snow} = a \cdot S^{b} \quad [dB/km]$$

Parameter for dry snow:

$$\alpha = 5.42 \cdot 10^{-5} \lambda + 5.4958776$$

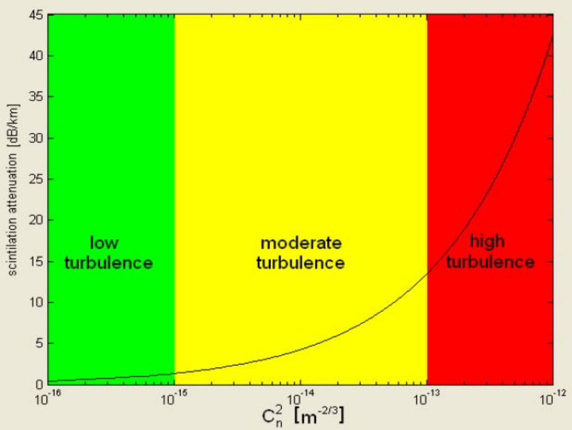
$$b = 1.38$$

Parameter for wet snow:

$$\alpha = 1.023 \cdot 10^{-4} \lambda + 3.7855466$$

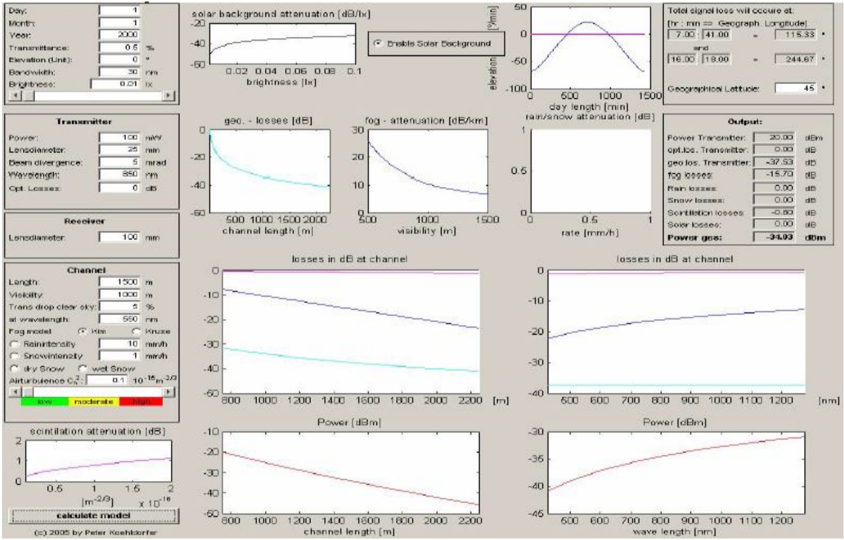
$$b = 0.72$$

Scintillation Losses



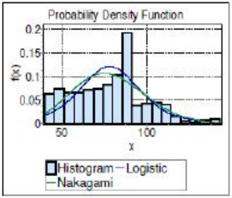
$$\alpha_{scin} = \sqrt{1.23 \cdot {C_n}^2 \cdot K^{\frac{7}{6}} \cdot l^{\frac{11}{6}}} \quad [dB]$$

Channel Modeling

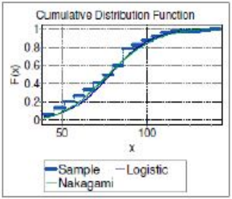


S. Sheikh Muhammad, P. Koehldorfer, E. Leitgeb, *"Channel Modeling for Terrestrial FSO,"* in IEEE ICTON, pp. 407-410, Barcelona, Spain, July 2005. [126 citations]

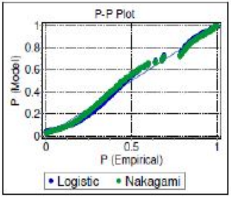
PDF Estimation of Received Signal Strength



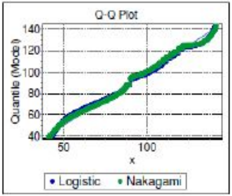
(a) pdf of the thick fog



(b) cdf of the thick fog



(c) P-P plot of the thick fog



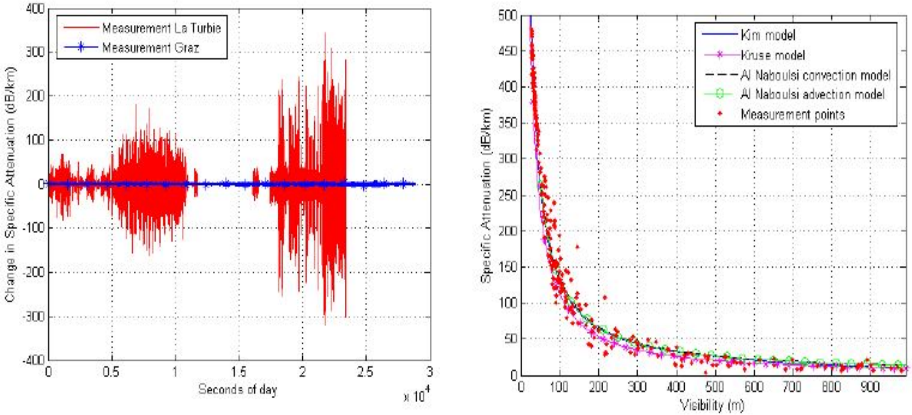
(d) Q-Q plot of the thick fog

Description	Distribution	Parameters
Thick fog	Logistic*	σ =11.79, μ =78.318
	Nakagami	m =3.5126, Ω =6591.0
Moderate fog	Johnson S_B *	γ=0.53036, δ =0.62405, λ =20.894 , ξ =19.886
	Wakeby	α =11.123, β =0.44992, γ =0, δ=0, ξ =19.693
Light fog	Johnson S_B *	γ=0.51767, δ =0.65162, λ =11.315 , ξ =9.2184
	Wakeby	α =6.1241 , β =0.48097, γ =0 δ=0, ξ =9.2025
General fog	Kumaraswamy*	α_1 =0.45233, α_2=1.6528, a=9.3395, b=236.09
	Gen. Gamma (4P)	k=1.0277, α =0.58616, β =62.564 , γ =9.3395

Tab. 5. Optimum parameters for selected Distribution.

M.S. Khan, M.S. Awan, **S. Sheikh Muhammad**, et al. *"Probability Model for Free Space Optical Links under Continental Fog Conditions,"* in Journal of Radio Engineering, vol. 19, No. 3, September 2010.

Fog Modeling for Terrestrial FSO Links



S. Sheikh Muhammad,B. Flecker, E. Leitgeb and M. Gebhart,

"Characterization of Fog Attenuation in Terrestrial Free Space Optical Links,"

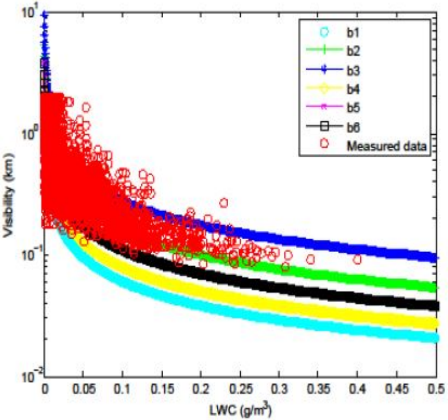
in Journal of Optical Engineering, vol. 46, No. 6, June 2007. [96 citations]

Models relating Liquid water content and Visibility

$V = b(\mathrm{LWC})^{-\frac{2}{3}}$,

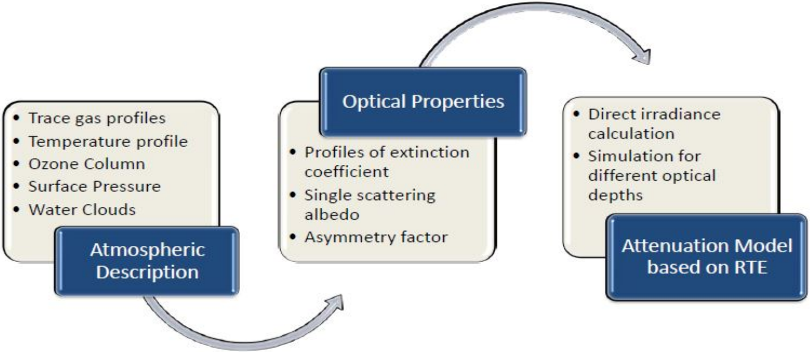
where V is visibility in km and "b" is a constant. The parameter "b" attains a different value for each different type of fog.

Fog Type	Value of *b*
Dense haze	0.013
Continental fog	0.034
Maritime fog (wet and warm)	0.060
Dense haze and selective fog	0.017
Stable and evolving fog	0.024
Advection fog	0.02381



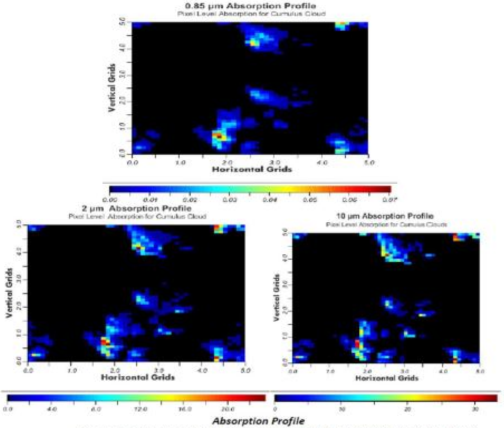
M. S. Khan, **S. Sheikh Muhammad**, M. S. Awan, E. Leitgeb et al. *"Further results on Fog modelling for Terrestrial FSO links,"* in Journal of Optical Engineering, vol. 51, No. 3, pp. 031207-1- 031207-9, March 2012.

Solution of Radiative Transfer Equation (RTE) to estimate optical attenuation for Satellite-to-Ground Links through clouds



M. Yousuf, **S. Sheikh Muhammad**, Z. Malik and G. Kandus, *"Cloud attenuation predictive model using solutions of Radiative Transfer Equations for Optical Feeder Links from Satellite-to-Ground,"* in proceedings at the Sixth Frontiers of Information Technology (FIT), Islamabad, December 2010.

Optical Propagation Modeling using Radiative Transfer Equation (RTE)



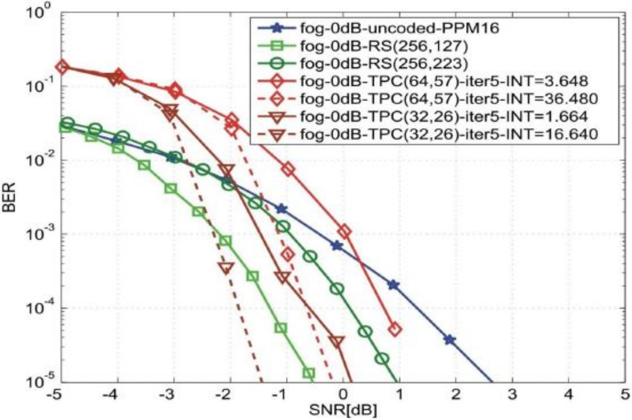
Absorption increases with the wavelength as 10 µm highly absorbs in cloud.

S. Sheikh Muhammad, Z. Malik and G. Kandus, *"Optical Propagation Modeling using Radiative Transfer Equation (RTE),"* invited paper at ICTON 2014.

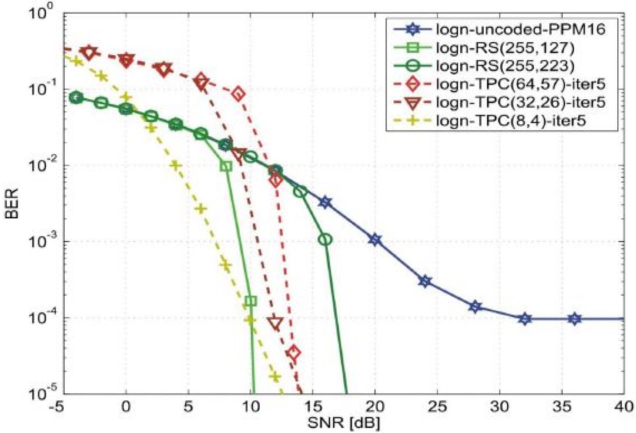
Coded Modulation

- Proposal and utilization of power efficient **M**-ary **PPM** modulation for Terrestrial FSO
- Comparison of Hard-decision and Soft-decision channel coded **M**-ary **PPM** performance
- Simplified Soft Value Extraction for **M**-ary **PPM** for the Turbo Codec
- SPW based simulation platform
- Turbo/RS codec designs

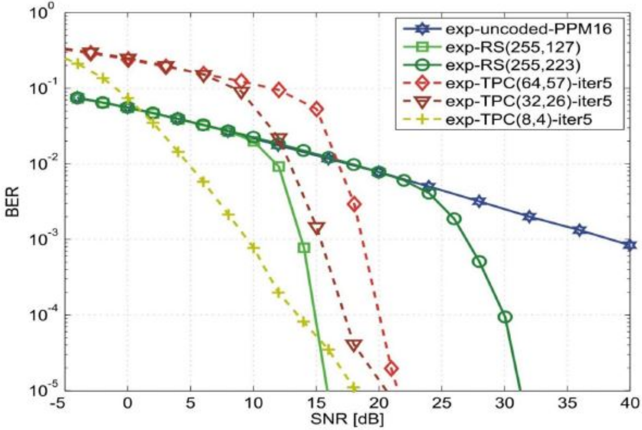
Coded Modulation performance for Foggy conditions



Coded Modulation performance in weakly turbulent atmosphere



Coded Modulation performance in strongly turbulent atmosphere



PPM Capacity Evaluation

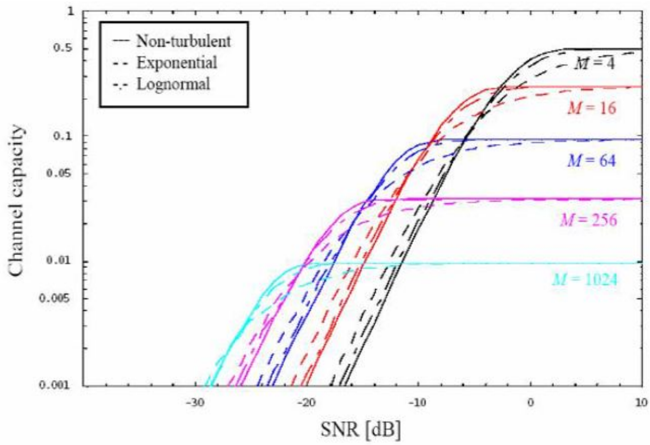
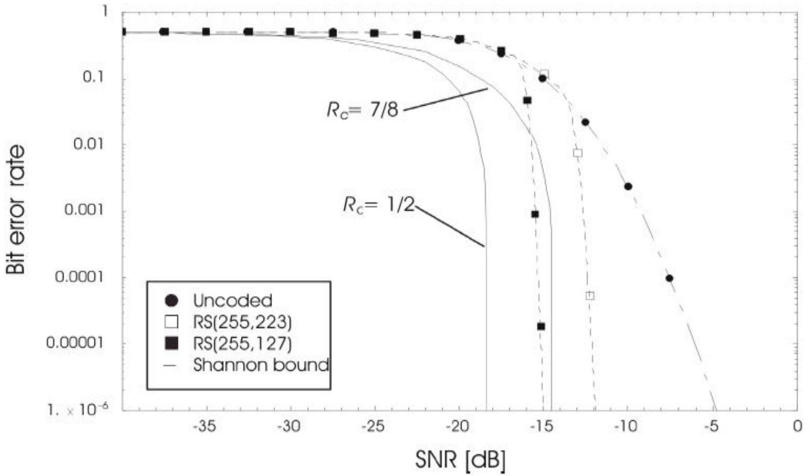


Figure: Evolution of $C_\circ$ with $n_b = 1$ and $\chi_{sc} = 0.25$

Shannon Capacity Limit Evaluation



W. Gappmair, **S. Sheikh Muhammad**, *"Error performance of terrestrial FSO links modeled as PPM/Poisson channels in turbulent atmosphere,"* in Electronics Letters, vol. 43, No. 5, pp. 302-304, March 2007.

Minimum Energy Bounds for Optical Wireless Relay Channels (OWRC)

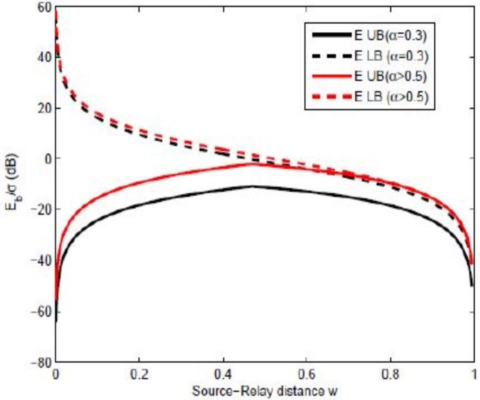
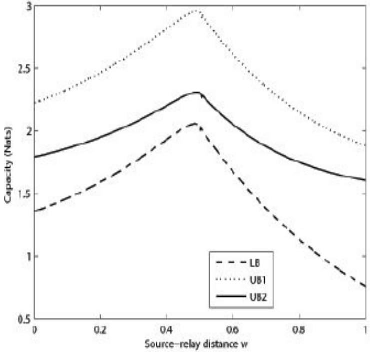
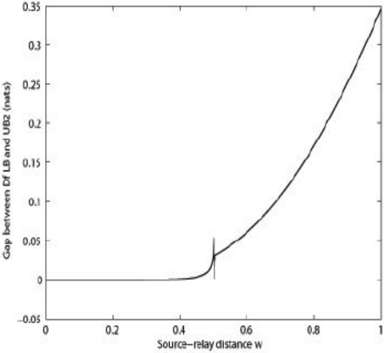


Figure: Bounds on energy per bit for an OWRC for the cases of $\alpha = 0.3$ and $\alpha \geq 0.5$.

A.D. Raza, **S. Sheikh Muhammad**, *"Bounds on Minimum Energy per Bit for Optical Wireless Relay Channels,"* Journal of Radio Engineering, vol. 23, No. 3, September 2014.

Capacity Bounds for OWRC





Upper and Lower bounds on the Capacity of mean and peak power constrained Gaussian Optical Wireless Relay Channel derived alongwith asymptotic behaviour.

A.D. Raza, **S. Sheikh Muhammad**, *"Capacity Bounds for a Gaussian Optical Wireless Relay Channel,"* in Transactions on Emerging Telecommunications Technologies (ETT), vol. 27, No. 7, July 2016.

Signal Estimation for the Gamma-Gamma Turbulence model

MMSE estimator

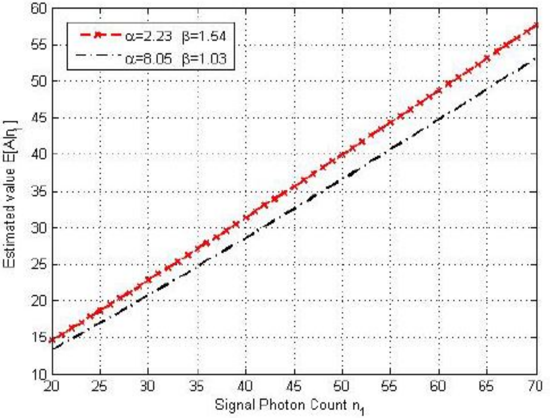
$$E[A|n] = \frac{(\alpha + \Sigma_{k=1}^{l} n_k)(\beta + \Sigma_{k=1}^{l} n_k)}{l} \frac{W - \frac{\alpha+\beta+1+2\Sigma_{k=1}^{l} n_k}{2} \cdot \frac{\alpha-\beta}{2} \left(\frac{\alpha\beta}{l}\right)}{W - \frac{\alpha+\beta-1+2\Sigma_{k=1}^{l} n_k}{2} \cdot \frac{\alpha-\beta}{2} \left(\frac{\alpha\beta}{l}\right)}$$

Upper bound on the derived MMSE estimator

$$E[A|n_1] \leqslant \frac{1}{\alpha\beta}(\alpha + n_1 + 1)(\beta + n_1 + 1)$$

S. Sheikh Muhammad, B. Rashid and A.D. Raza, *"Signal Estimation for the Gamma-Gamma Turbulence model,"* in Journal of Optical Engineering, vol. 52, No. 12, pp. 120501-1- 120501-3, December 2013.

Signal Estimation for the Gamma-Gamma Turbulence model



S. Sheikh Muhammad, B. Rashid and A.D. Raza, *"Signal Estimation for the Gamma-Gamma Turbulence model,"* in Journal of Optical Engineering, vol. 52, No. 12, pp. 120501-1- 120501-3, December 2013.

Interplay between Optical Wireless and Quantum Optics

- Quantum Information theory – evolving field
- Quantum Communication over long distances
- Quantum Cryptography – already tested on satellite links
- MLCD demonstration proves OWC utility on very large distance links
- Would OW evolve or merge into quantum communication???

Conclusions

- Digital communications adapted for Optical Wireless is evolving
- Network Information Theory applied to Optical Wireless provided new insight into Shannon limits of OW Relay Channels
- Radiative transfer elucidated Optical Propagation
- Optical Wireless need be studied in context of Quantum Theory???

Questions???